Modernizing the Machine Lab with Mechatronic Immersive Design and Artificial Intelligence

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Abstract

This paper presents the modernization of the Machine Lab, a creative studio that integrates digital control with the acoustic physicality of mechatronic musical instruments. Central to this update is the installation of a mechatronic instrument, an 8×8 array of Modulets mounted on the lab's ceiling, forming an immersive, distributed acoustic environment that enables high-resolution spatialized sound across 64 discrete locations.

Key architectural updates include the reintegration of Open Sound Control (OSC), enabling performers and composers to wirelessly network for flexible ensemble configurations. In addition, a novel AI-driven calibration framework is introduced using ChucK's ChAi library, employing a weighted ensemble of a multi-layer perceptron (MLP) and a k-nearest neighbor (KNN) model. This approach reduces the subjectivity of manual configuration of the mechatronic instruments while ensuring consistent dynamic response and timing accuracy across the Machine Lab.

Together, these updates position our collection of custom-built instruments as a scalable platform for immersive performance, pedagogy, and experimental research in mechatronic music systems, supporting both structured composition and exploratory, data-driven practices.

Keywords

mechatronic instruments, robotic music, network performance, machine learning, artificial intelligence, instrument calibration

1 Introduction

The Machine Lab [10] at the California Institute of the Arts (CalArts) is an experimental studio dedicated to the exploration of mechatronic instruments used in live digital orchestras. Traditionally, digital orchestras enable complex control and composition, where performance on laptops alone obscures the source of sound and limits the audience's perception of gesture. The Machine Lab bridges this divide by employing visible, physically actuated instruments that explicitly articulate the relationship between sound, motion, and space having been developed through the diaspora of the NIME community in the last two decades.

This approach was first publicly demonstrated by the KarmetiK Machine Orchestra [4], which premiered at REDCAT in the Walt Disney Concert Hall complex in Los Angeles in 2010. The ensemble featured custom-built mechatronic instruments, including MahaDevi [6, 7], GanaPati, and Tammy, performed alongside human musicians. The project presented a hybrid orchestral model in which mechatronic instruments were treated as expressive performers rather than playback devices. After touring internationally, these instruments were permanently installed at CalArts, forming the foundation of what is now known as the Machine Lab.

Consequently, this infrastructure catalyzed a specialized curriculum at CalArts designed to advance the field of musical mechatronics, including courses such as Interface Design, Robotics for Musicians, and Mechatronic Art. Ongoing research has led to the development of novel instruments, most notably MalletOTon and the Modulets. The development in the Machine Lab is a tribute to MacArthur genius Trimpin, who has worked with our community in the last two decades to explore and develop this art form [9]. This paper is organized as follows: Section 2 provides a technical overview of the Machine Lab's mechatronic instruments; Section 3 describes the updated network infrastructure; Section 4 presents compositional case studies.

2 The Mechatronic Instruments

2.1 Modulets

In Spring and Fall 2025, an 8×8 array of 64 Modulets was installed across the ceiling of the Machine Lab through the Mechatronic Art course, forming an evenly distributed acoustic canopy spanning the performance and fabrication space. This installation represents a significant expansion of the Modulet system previously introduced in an earlier NIME publication [5], in which a 4×4 grid of 16 Modulets was developed and evaluated as a modular, distributed audiovisual instrument. The current system scales that earlier design by a factor of four, enabling substantially higher spatial resolution and greater compositional and performative complexity.

Figure 1: Sample of Modulets

Each Modulet functions as an independent point of audiovisual sound production, combining mechanical actuation, acoustic resonance, and visual feedback within a compact, self-contained unit (Figure 1). A solenoid actuator strikes a custom aluminum casting, producing a bright, metallic timbre with strong transient characteristics. Integrated LEDs provide synchronized visual feedback tied to both actuation and control data, reinforcing spatial localization and contributing to an increased sense of immersion for performers and audiences.

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To support this large-scale deployment, a custom modular wiring infrastructure was designed specifically for the ceiling of the Machine Lab. Power, data, and mounting were organized using a grid-based wiring system, allowing Modulets to be evenly spaced and aligned while minimizing visual clutter and installation complexity. Each Modulet was designed to neatly snap together on both the instrument side and the control-board side, enabling rapid installation, removal, and reconfiguration. This approach preserves the modular ethos of the original 4×4 system while extending it to an architectural scale suitable for long-term installation.

In anticipation of sustained use over multiple years, we also fabricated a set of standardized spare components. This strategy ensures that individual Modulets can be serviced or replaced without disrupting the overall array, supporting longevity, maintainability, and iterative development. The system thus functions not only as a performance instrument but also as an evolving research platform for mechatronic sound art and integration to Machine Orchestra and other ensembles.

Beyond enabling high-resolution spatialization for performance, the Modulet array intentionally reflects the historical lineage of the Machine Lab. The violet illumination produced by the LEDs, combined with the purple anodized aluminum casings, directly references Trimpin's installation Conloninpurple, which has long served as a conceptual and aesthetic touchstone for the space. In this way, the Modulets acknowledge Trimpin's foundational contributions to the lab while extending the tradition of mechatronic sound art into a contemporary, immersive, and modular system.

2.2 Other Mechatronic Instruments

Figure 2: The MalletOTon.

In addition to the Modulet array, the Machine Lab houses six permanently installed mechatronic instruments. Table 1 summarizes each instrument's actuators, sound sources, and communication protocol, providing an overview of the physical and electronic diversity of the ensemble. Figure 2 shows the MalletOTon, a solenoid-driven marimba spanning the A2–C7 range, while Figure 3 depicts BreakBot and Lydia, which employ rotating brushes, motors, and a hacksaw mechanism to drive their respective sound sources. Together, these instruments span a range of actuation methods and sound sources, which are connected to the central server via Serial or MIDI interfaces.

Table 1: Mechatronic instruments in the Machine Lab.

Instrument	Actuators	Sound Sources	Protocol
MalletOTon (Fig. 2)	48 solenoids	Marimba bars (A2–C7)	Serial
Lydia (Fig. 3)	20 solenoids, 16 DC motors, hacksaw	Modified upright piano	Serial
BreakBot (Fig. 3)	Solenoids, rotating brush	Kick, snare, cymbals	MIDI
Tammy	Solenoids	Xylophone, plucked strings, bells	MIDI
GanaPati	Multiple solenoid mallets	5 plastic drums	MIDI
RattleTron	Solenoids	Hand perc., 3 metal pipes	MIDI

Figure 3: From left to right: BreakBot, and Lydia

3 System Architecture

Recent updates to the Machine Lab's infrastructure modernize the way performers and composers interact with mechatronic instruments. Figure 4 illustrates the system architecture, showing how a central server mediates communication between conductors, clients, and the ensemble of mechatronic instruments. Central to these updates is the integration of Open Sound Control (OSC) [12], which allows the system to communicate with any OSC-compliant software environment. As a result, users can compose and perform using a wide range of tools without requiring specific expertise in ChucK [11], while maintaining compatibility with the existing lab control systems.

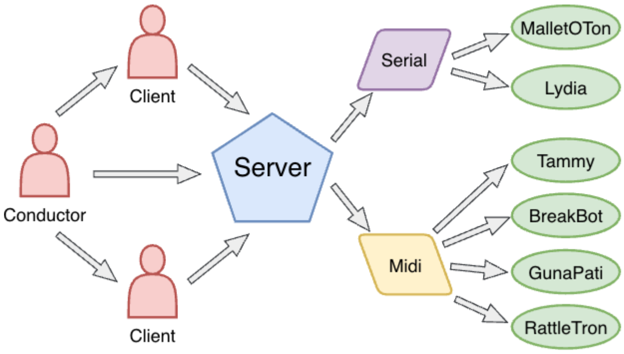


Figure 4: Machine Lab system architecture

3.1 Conductor to Client

To maintain temporal alignment, the architecture introduces a designated "conductor" role. The conductor is responsible for coordinating network communication and dynamically assigning ports to participating clients. This approach allows all clients to begin execution in a synchronized manner while remaining flexible to changes in ensemble size or configuration. The system leverages pre-composed ChucK scripts to manage this process, which are publicly available through the Machine Lab's GitHub repository.

3.2 Client to Server

The updated infrastructure supports multiple connection methods between clients and the server, including both Ethernet and wireless networking. Wireless connectivity expands performance possibilities by removing physical constraints imposed by available network ports. This enables larger ensembles and more flexible spatial arrangements, allowing performers to interact with the instruments from anywhere within the lab.

Clients communicate with the instruments by sending OSC messages to a server, implemented in ChucK, which routes control data to the appropriate mechatronic instruments. Messages follow a simple format consisting of an instrument name, a note value, and a velocity value, with the note and velocity expressed using standard MIDI ranges (0–127). Incoming OSC messages are routed to the appropriate instruments and simultaneously exposed on a monitoring channel, allowing clients to verify successful transmission and reception during performance.

3.3 Calibration

Recent software updates introduce a new calibration framework built using extensions of the ChucK programming language, specifically the ChAi [8] library. While ChucK has long served as the backbone for networking and instrument control in the Machine Lab, these additions enable machine learning techniques to be integrated directly into the performance environment.

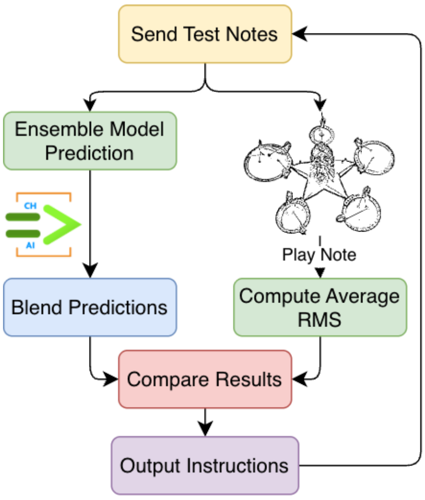
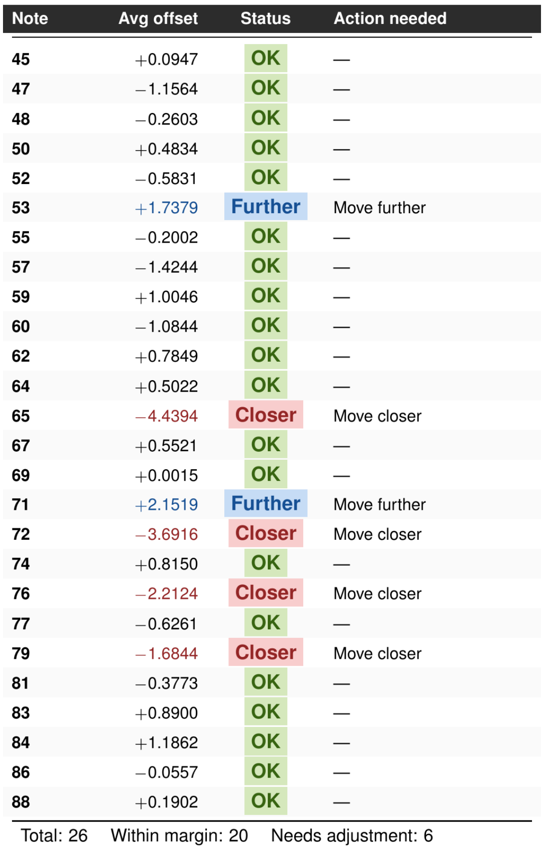


Figure 5: Ensemble calibration system using ChAi library.

Using the ChAi library, which provides interactive machine learning tools for ChucK, we developed a weighted ensemble calibration system that combines a multi-layer perceptron (MLP) [2] with a K-nearest neighbor (KNN) [1] model. The MLP provides strong generalization across unseen data points, while the KNN offers stable, data-anchored predictions based on prior observations. Together, these complementary behaviors make the ensemble well-suited for dynamic calibration for mechatronic instruments. Figure 5 illustrates the full calibration pipeline, demonstrating how the system iteratively sends test notes, blends the MLP and KNN predictions, and converges on a corrective output instruction through repeated comparison of results.

By automating calibration, the system eliminates subjectivity and inconsistency of manual tuning, ensuring consistent dynamic response across instruments. This approach improves reliability during performance and reduces maintenance overhead, allowing composers and students to focus on musical exploration rather than mechanical adjustment.



Note	Avg offset	Status	Action needed
45	+0.0947	OK	—
47	−1.1564	OK	—
48	−0.2603	OK	—
50	+0.4834	OK	—
52	−0.5831	OK	—
53	+1.7379	Further	Move further
55	−0.2002	OK	—
57	−1.4244	OK	—
59	+1.0046	OK	—
60	−1.0844	OK	—
62	+0.7849	OK	—
64	+0.5022	OK	—
65	−4.4394	Closer	Move closer
67	+0.5521	OK	—
69	+0.0015	OK	—
71	+2.1519	Further	Move further
72	−3.6916	Closer	Move closer
74	+0.8150	OK	—
76	−2.2124	Closer	Move closer
77	−0.6261	OK	—
79	−1.6844	Closer	Move closer
81	−0.3773	OK	—
83	+0.8900	OK	—
84	+1.1862	OK	—
86	−0.0557	OK	—
88	+0.1902	OK	—

Total: 26 Within margin: 20 Needs adjustment: 6

Figure 6: Calibration Results

The calibration pipeline generates a per-note offset report, which is printed to the terminal, saved as a JSON, and displayed as shown in Figure 6. Each entry reflects the computed mean offset and the corresponding corrective adjustment required to bring the mallet position within the prescribed ±1.5 JND tolerance.

The ensemble was evaluated using GroupKFold cross-validation across four chord-density configurations (9, 15, 22, and 26 notes). As shown in Figure 7 and 8, the hybrid model achieves lower RMSE and MAE than both baselines across most configurations — except for the 9-note RMSE, where the MLP performs best — and exhibits the largest gains at higher densities. Post-calibration, corrective offsets were applied to MalletOTon and all notes fell within the prescribed ±1.5 JND tolerance as reported in Figure 6.

3.4 Server Processing

The server is launched via a bash script that initializes the routing system and establishes communication with each mechatronic instrument. Instruments may be connected using serial or HIDUINO [3] interfaces. The current configuration supports seven permanently installed mechatronic instruments while allowing an arbitrary number of connected clients.

3.4.1 Pre-Processing. As displayed in Figure 9, Before performance begins, each mechatronic instrument performs a handshake with the server. During this process, the server receives a unique identification number from the instrument, which is then used to assign the appropriate OSC address and map the instrument to its corresponding USB port. This mapping determines how incoming messages are formatted and routed to each

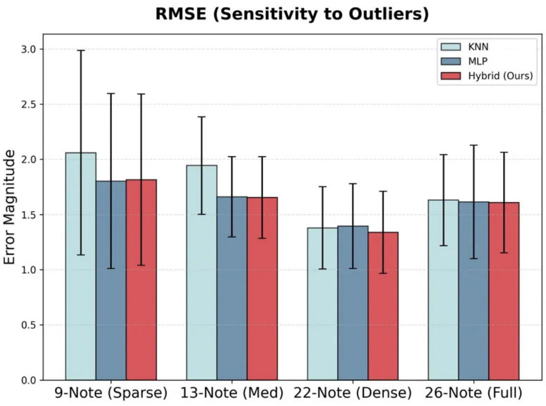


Figure 7: Evaluation Scores: RMSE

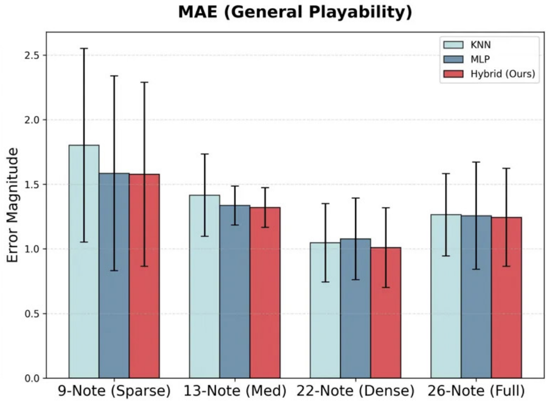


Figure 8: Evaluation Scores: MAE

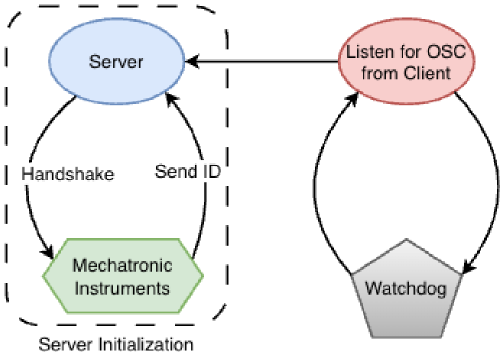


Figure 9: Server Pre-processing

instrument. Once the handshake and address assignment are complete, clients may begin sending control messages to the server. To protect hardware components, a watchdog system is implemented at the server level. If no activity is detected within a five-minute window, the server automatically disables active outputs to prevent solenoid overheating or burnout.

3.4.2 Main Processing. At the core of the system, a ChucK script functions as a centralized message-routing server. It receives incoming OSC messages, parses each message to extract the instrument name, note, and velocity, and then forwards the command to the appropriate mechatronic instrument using MIDI or OSC communication protocols.

For MIDI-based instruments, messages include standard parameters such as note number, velocity, note-on, and note-off events. Given the percussive nature of the instruments, a default strike duration of zero milliseconds is used to ensure that the beaters do not remain in contact with the sound-producing surface, which would dampen resonance. This duration remains configurable when longer contact is desired.

Instruments that use OSC communication follow a similar message structure, consisting of an instrument name, actuator identifier, and velocity value. All final messages are transmitted to Teensy-controlled instruments via wired connections to minimize latency between the server and the hardware.

4 Case Studies and Compositions

The updated system architecture has been integrated into the Machine Lab curriculum and is actively used as a performance and composition platform. Courses such as Machine Orchestra use the lab as a primary site for creative work, with students developing compositions that culminate in a public concert at the end of the term, seen in Figure 10. These performances also incorporate works from the Music Information Retrieval course, in which students create real-time visualizations that are displayed on the array of televisions installed throughout the lab. This integration encourages collaboration between disciplines and reinforces the relationship between sound, data, and visual representation.

Figure 10: Machine Orchestra Concert

The installation of 12 displays around the lab has further expanded its use as an immersive audiovisual environment. In Fall 2025, students in the Introduction to TouchDesigner course used the display system to present their final projects, transforming the lab into a gallery-style environment that combined generative visuals with spatialized sound.

Beyond fixed compositions, students have explored improvisational and generative performance systems. Many of these projects make use of the tools provided by the ChAi library. One example involves the use of hidden Markov models to generate chord progressions, melodic material, and rhythmic structures for performance on MalletOTon. These projects demonstrate how the updated system supports both structured composition and exploratory, data-driven musical practices within a shared performance environment.

5 Conclusion

The modernization of the Machine Lab bridges digital precision and acoustic presence through a combination of immersive spatial design and intelligent system architecture. The installation of an 8×8 Modulet array, along with an expanded ensemble of mechatronic instruments, transforms the lab into a distributed acoustic environment that supports spatialized performance while honoring its historical roots.

Updates to the system architecture—including OSC integration, wireless connectivity, and AI-driven calibration—enable larger ensembles, broader compositional tool-sets, and more reliable instrument behavior, while reducing barriers to interaction and maintenance within a complex mechatronic system.

The impact of these changes extends into pedagogy, where the updated infrastructure supports student work in immersive audiovisual performance, generative music, and machine learning–assisted composition. By functioning as both a performance venue and an experimental platform, the Machine Lab enables sustained engagement with mechatronic instruments across artistic, technical, and educational contexts.

Together, these developments position the Machine Lab as a flexible platform for ongoing research, performance, and education in mechatronic music systems. As new instruments, visualization tools, and intelligent maintenance strategies continue to be integrated, the lab remains an active site for exploring emerging forms of musical expression.

6 Ethical Standards

This work was conducted within the Machine Lab at the California Institute of the Arts as part of academic research and pedagogical development. The research focuses on mechatronic instrument design, system architecture, and machine learning–assisted calibration, and did not involve human subjects or personal data collection. All machine learning models were trained exclusively on calibration data generated from the mechatronic instruments themselves under controlled laboratory conditions. No personal, biometric, or proprietary datasets were used. The authors declare no conflicts of interest. This work was supported by institutional resources and facilities dedicated to research, education, and artistic practice.

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