A Conversation with Actuators: An Exploratory Design Environment for Hybrid Materials

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ABSTRACT

An exciting, expanding palette of hybrid materials is emerging that can be programmed to actuate by a range of external and internal stimuli. However, there exists a dichotomy between the physicality of the actuators and the intangible computational signal that is used to program them. For material practitioners, this lack of physical cues limits their ability to engage in a "conversation with materials" (CwM). This paper presents a creative workstation for supporting this epistemological style by bringing a stronger physicality to the computational signal and balance the conversation between physical and digital actors. The station utilizes a streaming architecture to distribute control across multiple devices and leverage the rich spatial cognition that a physical space affords. Through a formal user study, we characterize the actuation design practice supported by the CwM workstation and discuss opportunities for tangible interfaces to hybrid materials.

CCS Concepts

•**Human-centered computing** → **Interactive systems and tools;** *Systems and tools for interaction design;*

Author Keywords

Creativity support tools; Computational design; New Media

INTRODUCTION

The studio, the atelier, the kitchen, the laboratory, and the makerspace are sites of creative expression. Their physical layout reflects the identity of their creators, bearing a mark of the process and creativity of the maker, of how they think, how they work, and how they move their body. In these spaces, the role of computational design is emerging as a prominent element, yet its ability to adapt to physical workflows is limited.

For many creative practitioners, a computer in the workspace acts as an anchor [26], confining the body and mind from leveraging the rich spatial cognition that a physical space affords. Systems that incorporate digital elements in a physical space are inherently brittle [9], affecting their reliability and ultimately their use. Particularly frustrating for practitioners is how little physical skills and material knowledge transfers compared to the computational know-how needed to navigate the computational design space.

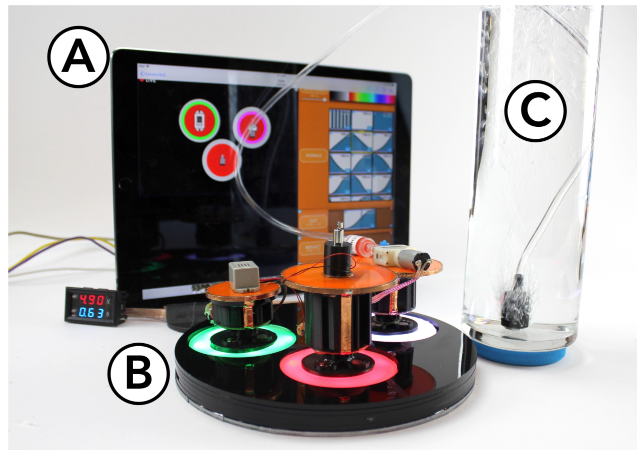

Figure 1. Conversation with Actuators Workstation. a) A digital design tool is used to both simulate, track, and stream data signals to a physical workstation; b) a physical workstation provides high-current power and digital control to ready-made capacitive touch-enabled stages; c) each stage supports interfaces to external materials.

How might a creative environment allow practitioners to work with and experience computation in the same way they fluidly work with physical materials? To explore this digital-physical boundary, we designed a hybrid workstation that facilitates working with actuators[1] controlled by a *digital* signal to produce *physical* changes in the environment via light, heat, motion, vibration, or pressure. The workstation is designed to support a thinking and working style common within physical practices known as a conversation with materials (CwM) [44]. The experience is characterized by materials taking on "a mind of their own," resisting or cooperating with the attempts of the practitioner to form them in a fashion that resembles understanding, persuading, and responding [11, 41]. However, for hybrid materials like actuators there exists a dichotomy between the physicality of the actuators and the intangible computational signal that is used to program them.

Our work aims to understand how design tools for hybrid materials can balance the conversation between physical and

[1]Actuation more precisely refers to physical motion; we use this term to refer to the range of possible physical outputs.

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digital actors. In this paper, we first ground our discussion of a "conversation with materials" through an exemplar and motivate a set of design principles for facilitating a *conversation with actuators*. Through a formal analysis, we distill the conversational profile of actuators, identifying five material actors, both digital and physical. We then describe a workstation that foregrounds these actors and enables users to send digital signals to actuators through touch interactions. Lastly, we present the results of a formal user study and characterize the actuation design practice supported by the workstation.

RELATED WORK

We review work in design theory and systems research that explores how computational practices can facilitate working with digital and physical materials.

Supporting Material Practices

A large body of work derives from Schön's concept of reflection-in-action, an act of thinking and reflecting on action so as to influence future action [44]. This back and forth between designer and medium elicits a conversational relationship [53]. Many creativity support tools have been developed to foreground this conversation. To enable interactive device design development, d.tools [14] aligned its workflow with the design, test, and analysis of a reflective prototyping cycle. The conversation metaphor has also been explored explicitly as a dialog where an agent (a digital screen with a talking face) elicits reflection in the course of a design session [20]. More implicitly, artifacts that incorporate "slow technology"(e.g., [35, 34]) more naturally influence reflective behaviors.

Within HCI, discussions of materiality have grown from advances in physical computing and material science innovations [39]. Giaccardi and Karana [12] introduced a framework for articulating how materials participate in the making process, identifying four experiential levels: sensorial, interpretive, affective, and performative. Schilling et al. proposed discriminating the focus and attention of materials actors over time as a method of characterizing the "talk-back" that occurs during a creative session [42]. Our work builds on this discussion through the design of a physical system that gives a stronger physicality to digital actors.

Supporting Working with Hybrid Materials

Smart and hybrid materials have expanded the landscape of creative artifacts and experiences, yet their co-existence with digital and physical ways of making produce several tensions. As new materials emerge within existing practices, Nitsche [33] observed the necessity of building on the material basis of the particular craft and rooting interaction in the complex interplay of materials. Vallgårda and Redström [51] advocated for the notion of computational elements as containing many of the same characteristics as physical materials such as substance, structure, and surface. Extending the concept of a computational composite, Liu et al. [28] describes smart materials having the ability to "[alter] a passive, static conversation into an active, sensorial interaction." Early work in hybrid craft introduced the idea of “conduits” or devices for transferring programs to physical media (such as a wand that transfers behaviors to objects) to facilitate interactions with hybrid media [4]. Such conduits are explored as a form of material programming with physical tools [50]. Digital materials complicate a conversation with materials, lacking a rich sensorial interaction that is central to a conversation with materials. Our work extends existing actuation design practices to interface with a wider range of materials, externalizing these 'conduits' as infrastructural, tangible elements in a creative space designed to facilitate the unique concerns of both physical and digital formal elements.

Exploratory Environments and Actuation Design

Digital signal design has been a successful area supporting a variety of users and domains such as new media practitioners and flow-based programming (e.g. Max/MSP [38]), nonprogrammers and graphical simulations (e.g. LabVIEW [52]), or with children and tangible program-by-example (e.g. Topobo [40]). Other computational design practices leverage sketch-based interactions: Schneider et al. [43] demonstrate the additional flexibility of encoding actuation behaviors for vibration with spatially-aware vector representations. Sketch-based annotations have been further used to define how graphical elements move in virtual space, exposing time and space as formal variables within animation [22, 23], and encode optimized geometries for light displays [47] and mechanical linkage systems [24]. Similarly, firework [2] or Christmas light [1] displays encode the repertoire of the practice, incorporating mechanisms for choreographing control across multiple actors. Our work builds on these practices, introducing a decentralized streaming architecture that allows different devices to control and compose digital signals and make use of the spatial cognition afforded by physical, creative spaces.

CWM DESIGN PRINCIPLES

To better ground our discussion of what facilitates a Conversation with Materials, we draw on the exemplar of clay situated within a ceramics studio and contrast it against actuators in an electronics design practice.

1. Expose a rich, responsive conversational profile

Clay exhibits multiple methods of conversing; as a physical material, clay can readily "talk back" through its sensorial profile. For example, to communicate its workability, clay redundantly communicates through a variety of sensory channels: visually, it displays its wetness and dryness; haptically, it responds to interactions with hands and tools; olfactorily, clay particles become suspended in the air. Even an awareness of the time spent in open air guides how ceramicist structure their creative process. As part of a long tradition, clay can converse symbolically through the cultural significance of its origin, or self-referentially through engagement with a set of methods, motifs, or artifacts within a particular practice. The sensorial interaction that clay exposes informs creative process.

Actuators have their own sensorial profile. While the rote capabilities of an actuator such as a motor are well-understood, working directly and actively with a motor exposes not only the motion it generates, but the sound and vibration it produces, the range of its speed, the extent of its torque on other objects, its presence in an environment, and the limits of its ability to transduce an electrical stimulus. However, the effort needed

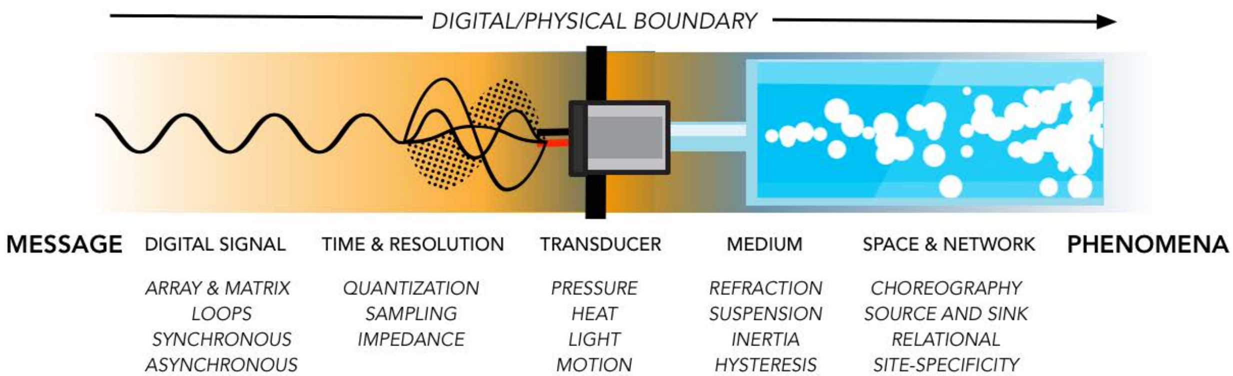


Figure 2. Formal elements of a bubble display. Sampling a sine wave function forms a digital signal, which is stored as an integer and converted to an analog signal. The electrical signal is transported through a wire, distorting and acquiring noise. While the air pump is off, water fills the tube connecting it to a tank. This exerts an extra torque on the motor, increasing its internal resistance, and drawing more current. The signal is transduced, changing the internal air pressure and driving air through the water medium. The hysteresis of the medium causes the periodicity of the original sine wave to converge, forming groups of bubbles, propagating down the length of the tube, driven by buoyancy forces to escape towards its outlet, forming the final experienced phenomena.

to appropriately house, power, and program actuators limits this type of conversational interaction [13].

A CWM experience should communicate state and affordance, across both physical and digital materialities, through responsive multimodal interactions. Formal elements should be readily interpretable as creative agents.

2. Support a constructionist learning experience

The ceramics studio facilitates a conversation through the versatility and ubiquity of the clay form — clay can exist in a variety of form factors (e.g., slips, slabs, coils), allowing for a body of techniques and methods to develop around a form-factor. Slip-casting, a technique where a liquid clay body is poured into a mold and allowed to set to and form a shell, is transferable across many material practices (e.g., chocolatiering, silicone molding). Instruction in such a space is fundamentally constructionist, where the ability to converse is developed through exploration, practice, and exposure to materials. The ceramics studio facilitates a conversation with clay wherein mistakes and accidents can be reconstituted and reclaimed using a pugmill and clay mixer, reducing the economic and emotional costs of engaging in a conversation [48].

In physical computing environments, the conversation is relatively expensive. Support for physical debugging is particularly limited [5], with more critical errors occurring across digital to physical translation. Programming is additionally complicated by the time-consuming need to flash code to microcontrollers, limiting exploratory behaviors in favor of attaining a minimal viable product.

CWM environments should minimize the cost of exploration and allow the user to extract meaningful information or knowledge at any point during the workflow.

3. Degrading gracefully

In concert with the vision of ubiquitous computing for computation to recede into the background, cyber-physical systems still require maintenance and repair. Relying too heavily on centralized systems introduces significant risk should they breakdown. A single loose wire should not break the entire interaction, nor should it disrupt a workflow. In a ceramics studio, a pottery wheel may break down, but it does not restrict the ability to continue using other clay-forming techniques.

Systems in creative spaces need to communicate their seams [6] and be designed to degrade gracefully, maintaining some level of functionality at all times in the case that different components become unstable.

CONVERSATIONAL PROFILE OF ACTUATORS

To identify the conversational profile of actuators, we conducted a formal analysis [32, 3] to distill how form-giving elements are “arranged and function within a composition"(Figure 2). We specifically delineate the different established traditions and practices that influence each of these formal elements within New Media, art practice, interaction design, and HCI communities. We limit the analysis to actuation that is produced from a digital signal and reserve the much larger space of analog signal design and actuator-sensor design as an area of future exploration. Depicted in Figure 2, we present these formal elements in a linear order, beginning with the message, or concept, progressing through its evolution as a signal, and ending with the phenomena produced.

SIGNAL

The digital signal is commonly expressed as a time-value pair, encoded as an array. The array as a digital material affords certain manipulations such as in-order atomic traversals, affine transformations, and interpolation. These manipulations produce unique artifacts to the signal constituting a characteristic digital aesthetic [15, 29, 51], namely: *atomicity*, that activations of the material occur with binary precision; *resolution*, or the error that arises from discretization and quantization during analog/digital signal conversion; *random-access*, also *indexability*, or the ability to access information without temporal or spatial restrictions; and *structural artifacts*, or the data structure present in the physical materialization of the digital material such as the pixel. Working with digital materials lowers risk, instead prioritizing interactions that reuse and repeat [29] as well as fragment and recombine [15].

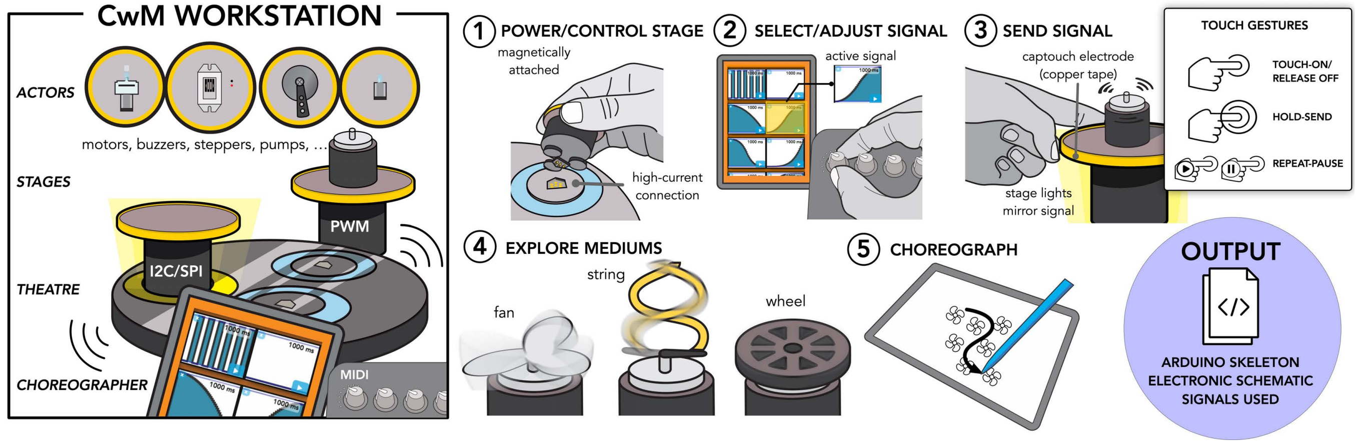


Figure 3. A Conversation with Actuators. A physical workstations uses stages to interface with actuators. These stages dock to a central power station which exposes a websocket API for communicating with and controlling signals sent to actuators. 1) Embedded magnets allow for quick attachment to a high-current power source; 2) different devices can be used to select and adjust a signal; 3) a capacitive electrode is wrapped around the stage and senses touch events; these events trigger the active signal to be expressed by the stage. An LED ring under each stage mirrors the signal being sent to the actuator; 4) stages provide interfaces to external materials to gauge the characteristics of actuation; 5) a live representation of the scene is used to specify how a signal is sent to multiple actuators. Design files can be obtained at any point in the process.

TIME & RESOLUTION
As a signal travels through a transport layer (e.g., wire, open air), its resolution and period mediate how it arrives at the transducer. Time and resolution can affect the original signal through sampling error: signals may degrade and quantize from undersampling, fold from sampling at the Nyquist frequency, or exist in an anti-aliased form. While many systems remove noise and sampling artifacts, the incongruency between bandwidth and temporal resolution is a defining characteristic of early and current digital material practices that has given rise to several expressive and culturally significant media forms such as the pixel [16], the "8-bit aesthetic" [7] (e.g. chiptunes [21], bitmap art), and the glitch [31, 19].

TRANSDUCER
A transducer sits on the digital/physical interface and can be used to refer to sensors or actuators. For actuators, a transducing element converts an electrical signal into light, heat, smell, sound, pressure, or motion. Each transducer has a unique conversational profile characterized by its physical and mechanical profile (e.g., response times). Within interaction design, these different profiles are leveraged to communicate information in the cognitive background (see ambientROOM [18]). Within each modality, a domain-specific vocabulary of behaviors exists, each with a narrow bandwidth of communication.

PHYSICAL MEDIUM
The transduced physical stimulus is attenuated through an additional physical layer which we refer to as the medium. Various principles exist for expanding the legibility of the physical stimulus. Most prominent is the concept of "the medium is the message", a term popularized by McLuhan [30] used to describe how the content to be displayed (the message or signal) is inextricably tied, influenced, and altered by the medium that is used to transmit it. For heat, the thermal properties of materials define how heat is experienced over time. For light, reflectors and diffusers affect its presentation. For motion, linkages, gears, and other mechanical mechanisms can be used to amplify and redirect motion.

SPACE & NETWORK
Actuators exist within a certain space and communication network. Spatial relationships can defined both physically and virtually (e.g. the range of a wireless network) causing actuators to form relationships and cliques. Work in HCI [23, 16] and New Media [46, 49, 25] has explored interactions that arise from these spatiotemporal relationships. Similarly, the context of the space can be leveraged to further alter the message, enabling distributed behaviors and control for constructing large collective displays [45, 10, 8, 27], or as site-specific constructions (e.g. urban street lighting [36]).

SYSTEM DESIGN
In this section, we present a high-level overview of system components, annotate the design decisions that facilitate the conversational profile of actuators, and provide some implementation details. The workstation is designed as a piece of infrastructural equipment, similar to an oscilloscope, that is maintained and used within a communal space[2]. Figure 3 depicts the workstation and a typical interaction with the station, comprised of three elements:

- **THEATRE** - a central docking station exposes a common set of connections for ID, high-current power, a pair of GPIO pins, and a capacitive touch electrode. Each docking site is surrounded by a ring of smart LEDs, or *stage lights*, used to communicate system state. An application programming interface (API) exposes points to query or alter the theatre state via websockets.
- **STAGES** - modular, peripheral components magnetically attach to the theatre. The role of the stages is to house, showcase, and facilitate the exploration of the unique properties and design concerns of an actuator.
- **CHOREOGRAPHERS** - interfaces that facilitate communication between actuators connected to the theatre and the user. Choreographers were implemented as a web application and as a physical MIDI controller.

[2]The station design has been made available open source: https://github.com/Hybrid-Ecologies/a-conversation-with-actuators.

Design Decisions

We examined how the workstation could increase the visibility and expose handles for creative control for each actor in an actuator's conversational profile (Fig 2).

Since the qualities of the SIGNAL are strongly tied to a synchronous programming workflow, we chose to allow users to issue actuation commands asynchronously through a streaming architecture. Asynchronous communication allows for multiple devices to act as signal generators; additionally, it prevents blocking code. For instance, commands for a stepper motor and an LED are interleaved, allowing both actuators to be controlled at the same time. We leverage the streaming architecture to generate and manipulate signal through different devices (Arduino, MIDI controllers, web applications). A MIDI knob, for example, could control the position of a stepper motor. With multiple devices capable of controlling actuation, communication is not delegated to a central point source but instead distributed throughout a space.

Once the signal is transmitted, it is susceptible to TIME & RESOLUTION and altered by the properties of the TRANSDUCER. For example, sending a sine wave to a motor produces an altered representation from both hysteresis and inertia. Since LEDs are the least susceptible to these actors, we use them to present a more faithful representation of an undistorted signal. Any signal sent to a stage is mirrored in the corresponding stage lights. A user can then compare the undistorted signal against the actuation expressed, exposing both noise and sampling artifacts as well as a transducer's profile.

The stages were designed to house actuators and facilitate interactions with different MEDIUMS. For example, a LIGHT STAGE would house LEDs in a recessed reflective cavity. A collection of interchangeable diffusing materials could then be used to explore different light textures. A VIBRATION STAGE would provide a collection of sound dampening or attenuating materials. A PNEUMATICS STAGE would provide connectors, valves, and air tubes to interface with balloons, water, and other mediums. The types of stages in the makerspace would reflect the unique repertoire of actuators that are available; the expertise of the community could additionally be reflected in the collection of exploratory mediums.

As opposed to designing actuation in isolation, the choreographer provides a user more nuanced control over how a group of actuators within a SPACE & NETWORK interact with each other. The choreographer allows users to specify a high-order behavior (e.g. turn on from left to right) by drawing a vector path. Actuators are then ordered based on their projection onto the vector and sent a signal in turn. For a circular LED ring, a zig-zagging path would cause a interlaced LED behavior to be expressed (Figure 4).

SYSTEM ARCHITECTURE

Theatre Dock. Actuators require more current than most microcontrollers can supply; a transistor or relay connected to an external power supply is typically used to supply the requisite current. In this configuration, the microcontroller serves only to supply low-current logic to trigger transistors or relays to activate and drive high-current actuators.

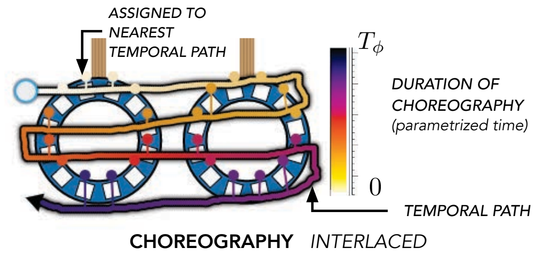


Figure 4. Choreographed signals. Drawn arrows are used to specify when an actuator receives a signal over a period of time.

The electrical design for the CWM workstation follows this pattern (Figure 5): an Arduino (atmega32) microcontroller is used to generate a logic-level signal which is amplified using n-channel "low-side" MOSFET transistors (P30N06LE) connected to an external high-current power source. Although an Arduino can produce PWM signal, we connect an external 12-bit PWM driver board (PCA9685) to the I2C bus, freeing up microcontroller timers and processing to instead be delegated to processing serial communication.

The theatre was constructed from a custom two-layer PCB designed to route control and power to all components. The theatre served as a breakout board to then be connected to a form factor for housing stages. Sets of six pins were exposed through the theatre: a high-current PWM signal, a common ground, two general purpose input/output (GPIO) pins, an ID pin specified through a unique voltage divider circuit, and an electrode routed from a capacitive touch controller (MPR121).

Theatre API. The theatre implemented an event listener for dock changes (when a stage is moved in or out of a docking site) and capacitive touch changes (touch and release); it additionally exposed API points for changing the PWM frequency being sent to each dock, and changing the color and intensity of the dock LEDs. Our system processed bi-directional `UART` serial information from peripherals coordinated through a middleware server (`Ruby EventMachine`) accessible via websockets. The input and output streams of devices were exposed to applications as subscribable services.

To introduce this functionality to off-the-shelf Arduino devices, we supply a library that provides streaming functionality without interfering with programming logic, minimizing the footprint of incorporating this architecture into current physical computing practices. With the addition of a Bluetooth Serial interface (e.g., HC-06, JY-MCU), the system additionally supports mobile interactions.

Stages. Stages are held to the theatre dock magnetically (Figure 5). A 3D printed enclosure holds a custom PCB, 6 pogo pins and 3 neodymium magnets that pair with a symmetric configuration on the theatre board. The PCB is configurable to match the needs of a specific actuator. In its simplest form, the PCB exposes only the load power and ground pins, allowing current-driven devices (e.g., piezos, motors, LEDs, buzzers) to be connected to the system. Alternatively, the two GPIO pins can be used to communicate via an I2C or SPI protocol. Each stage has a touch-enabled surface enabled by wrapping copper tape along the edge of the stage and connecting it to the capacitive touch electrode.

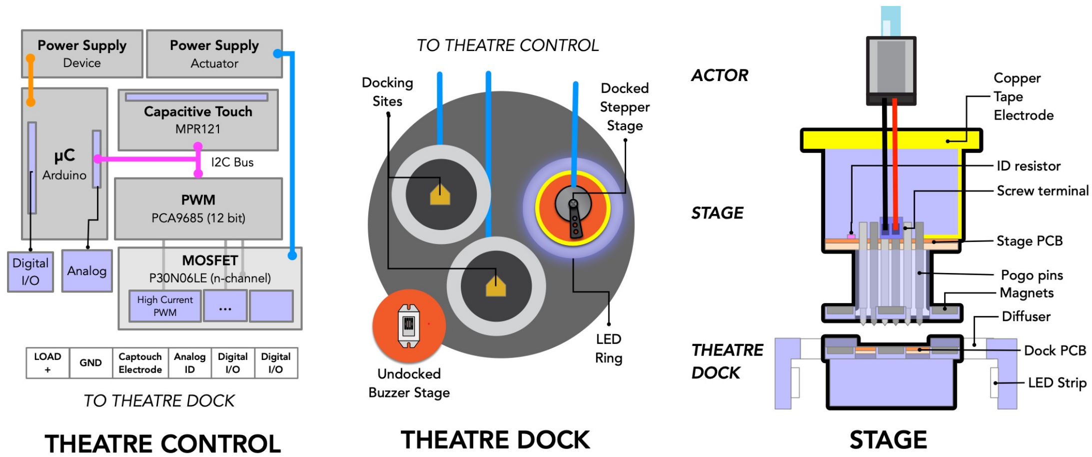


Figure 5. System architecture. The theatre control board exposes a common set of electrical connections for digital control, high-current power, and capacitive touch. A PWM signal generator is used to trigger high-current gates. These connections are routed to a docking station where stages are magnetically held in place. Six pogo pins in the stage route electrical connections to the facilitate the unique needs of a target actuator.

The stage can be configured in one of four touch interaction modes. A *tap-on* mode would send a high signal on touch and a low signal on release; should the system be reduced to only the theatre/stage, the CwM station would assume this mode allowing for its continued use degrading gracefully. A *hold-send* mode would send the active signal only when a stage was being pressed required users to actively touch and perceive the stimulus coming from the actuator.

Choreographer Web App. A web application running on an iPad was used to select, compose, and adjust data signals sent to a target actuator (Figure 3-2). The application subscribes to TheatreEvents via a websocket and keeps a live, updated representation of the elements connected to the theatre, presenting it visually through an SVG representation. Data signals are presented as manipulable visual blocks that are sortable and composable along a time track, following the visual metaphor and direct manipulation interactions common within video editing and sound composition design tools. The data signal is internally represented as a sequence of commands $\tau = \langle t, I \rangle$ where t is the desired time (ms) of execution and I is intensity. Externally, the blocks can be configured to display the signal as a line graph, as a hue, or as a position. These signal blocks could be composed through track operations (Figure 6) including concatenation and separation (**WELD**, **CUT**) or transformations (**REFLECT**). We include an initial sampling

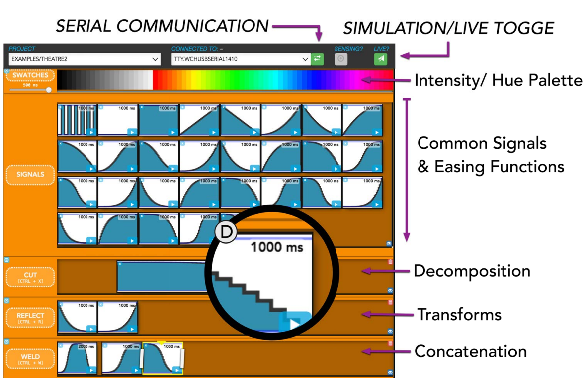


Figure 6. A library of common signals are displayed on a mobile web application. Signals are sent to the theatre via websocket communication.

of common signals (on, off, pulse), and a series of common easing signals (e.g. linear, cubic) used in motion design.

Choreographer-MIDI Controller. A MIDI controller with 8 touchpads, each with 2 associated knob controllers, is connected to the theatre via a websocket. It coordinates with the web application to allow users to delegate a pad to store and playback a specific signal. Knobs were used to control playback position and signal duration.

EVALUATION

The goal of our user study was to understand how foregrounding digital and physical actors alters the design decisions taken by practitioners. We survey the current repertoire of actuation design practices, evaluate the usability of the system, and describe the material conversations that occurred with the system.

Participants. The study was conducted with 18 novice interactive device designers (avg. 22 years, 8 female, 10 male, 0 nonbinary) with previous exposure to electronics recruited from university mailing lists in Art, Architecture, Design, and Computer Science. Proficiency was self-reported in a preliminary survey; all participants indicated experience working with actuators.

Study design. Participants were invited to meet with us in our studio space for an hour-long workshop and paid $20/hr. Each session surveyed participants on personal actuation design practices; a warm-up tutorial; a think-out-loud with a series of exploratory design tasks; and a post-study interview. Participants engage with the system in one of two configurations:

- *Multimodal*. Participants were exposed to three stages containing a buzzer, a vibrotactile motor, and an air pump connected to an airstone submerged in water; participants were tasked with brainstorming designs that incorporated any of these elements.
- *Multi-actor*. Participants were exposed to a non-matrix 25 RGB LED display and asked to design an ambient display for a high-energy location (e.g., parade, hospital ER, nightclub) or a low-energy location (e.g., park, beach).

RESULTS

We report survey responses and qualitative results from participant interactions with the workstation and interview responses. We synthesize common themes and insights to support the design of future tangible interfaces for hybrid materials.

Survey Results: Complexity drives opportunistic actions

In our initial survey, participants reported experience with a variety of interactive devices including RC cars, art installations, lighting displays, and robotics. Actuators were used for their rote purpose, as a spectacle element, or for communicating information. Software complexity was the chief deciding factor that influenced decisions on how actuation was used in personal projects. All participants reported major challenges with the Arduino programming experience. While it had helped them enter the physical computing space, the perceived time requirements to develop more complex actuator behaviors was prohibitive, and most users left even functional actuator design to the very end:

> **P5** With software, you have to put enough time to understand what you're doing, and I just don't have time. But I don't want to just take code from StackOverflow because it feels like cheating.

Actuators used as system state indicators were often directly mapped to sensor values to minimize complexity; legibility remained a common issue.

Experiential encounters drive conversations

Each participant explored the station differently, guided by the most salient material actor. For the multimodal task, a majority of participants gravitated towards the unique sound that each actuator produced. Participants attributed proclivity to their perception of the capacitive touch interaction as that of a DJ, reinforced by the use of a MIDI controller commonly used in such performances. Other participants were drawn to the signal design interface, finding familiarity in the waveforms, specifically recalling and attempting to emulate the common yet evocative fade-and-pulse behavior.

Others were captured by the unfamiliarity of the air pump, attempting to decipher the blackbox around the transducer mechanism or the strangeness of an open bottle of water next to electronics. Few participants could interpret the nature of an actuator by sight, but all participants had encountered them before and could immediately recognize them through their expressions.

Conversations elicit memory and evocation

Many participants were uncomfortable sending signals to the buzzer, initially avoiding it completely. However, its unique semiotic association to alarm clocks made it an evocative stimulus. As participants experimented with other actuators, it built familiarity and confidence to test the signals with the buzzer.

> **P12** Oh! [touching and startled by the buzzer] This... this is the sound of a toy train my grandpa used to have. And people would drop it because they were startled.

The responsive feedback from the system drove participants to create noises, searching for and responding to sounds that evoked laughter or a memory, speculating on which touch-triggered sound to incorporate in personal projects that would otherwise remain static.

Immediacy of feedback builds reliability

Exposing the capabilities of the actuators drove exploration. Overall, participants considered the CwM station to be characterized most strongly by the immediacy of feedback from touch, by the lights, or through the SVG simulation. In particular, the visual-forward interface better represented the materials at hand.

Notably, one participant decided to explore the physical medium, cutting impromptu fan blades from styrofoam, modeling their design against a nearby fan. Placed on the shaft of the vibrotactile motor, the participant sent a high signal to the stage. The stage lights flashed, indicating that the signal had been sent, yet the fan had not moved. The participant repeated sending the signal without success. He removed the fan blades and transmitted the signal without it, surprised at the vibrotactile motor whirring to life. He realized that the fan, positioned too close to the end of the motor shaft, produces more friction than the motor can overcome.

Another participant contrasted their experience of encountering a similar difficulty: she was unclear whether the actuator was defective or misconfigured, abandoned the attempt and moved on to use a different component. For her, the workstation "removed the guesswork" and confirmed the validity of her design. The value of immediate feedback allowed both participants to recover and constructively build an understanding of the limits of the actuator.

Streaming commands enables design complexity

While participants reported that the task was a comfortable fit with their current experience level of programming, they thought that creating a similar effect, especially with the number of actuators and other components in the system, would be incredibly tedious to accomplish without the tool (P9: "It would take me a month!"). In considering how they would create their finished designs in Arduino code, participants universally anticipated a dramatic increase in difficulty:

> **P3** [Programming that same interaction] in Arduino would be terrible. I'd have to manually put in all of the different values, and it would be really difficult to keep track of all of the values. For loops would also be annoying especially since there are so many different regions that you're controlling at the same time, so I think programming it would be a complete mess.

> **P1** It would be painstaking, and a real annoyance, but you could do it...That would be a whole bunch of loops, and yeah I wouldn't want to do that.

For the multi-actor condition, several users focused on the hue, saturation, and brightness of the LEDs, exploring the possibilities of working with these elements in ways that differed dramatically from the binary on-off typically used in their personal projects. Participants were surprised by how subtle timing differences dramatically altered choreographies.

By the end of the workshop, users found the choreography control to be appealing with more than half incorporating it into their final design. This evolving relationship to the formal elements of actuators demonstrates the importance of exposing the conversational profile as a means of enabling creativity.

We see the conversational model the workstation affords as clearly supporting a more exploratory process that enables complex designs and supported an exploratory design workflow, even with the additional complexity of driving many actuators.

New vocabulary reflects deeper engagement

Participants with a stronger programming background initially found the tool challenging their existing mental model of design-programming (e.g., **P6**:I want to toggle each one individually.) In probing mental interaction models, we found consensus in how users approached manipulating LEDs (and other actuators) by using an array or matrix, going as far as having the virtual form dictate the design.

> **P3** My approach would probably be to figure out how to identify each individual LED, then run the cycle of light changes ... and just iterate through all the IDs in the right order.

We argue that the new mental models introduced by the tool caused users to shift from this thinking, focusing instead on the design rather than the underlying architecture. As they gained familiarity with the tool and began generating spatial designs, we noted a shift in think-out-loud language. In particular, participants described their workshop creations and practice in spatial and relational terms, using the choreography to program their desired spatially-meaningful messages, with their language mirroring the effect they wished to communicate.

> **P7** It looks scattered, or maybe the concentricity is a little too prominent, and I want it to be a little subtler. As far as getting someone to tap that, it's drawing me toward [the center]. Then for more visual effects there's really more emphasis on the pulsing.

Several engaged with the more conceptual thinking behind what the actuation was doing, and the context of the environment.

> **P5** It would make things a lot easier than just writing code, especially for people who are more visual design focused and less software focused like me. I know enough software technicalities to think of algorithms, but I don't necessarily have the skills to implement them as I want them to, so this provides a bridge between what I want to happen - the conceptualizing step - and the actual "making-this-happen" step.

Additionally, users continued to identify as authors despite the automatic code-generation of the workstation, and did not view this generation as taking away from the design process.

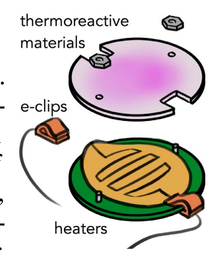
DISCUSSION

As digital fabrication evolves, we aim to bring many of the same familiar fluid elements of creativity found within the established artistic practices to this domain in the hope that such efforts will broaden participation, improve inclusively, and enable new forms of creativity, innovations, products, and art. From our user study, we observed how defamiliarizing standing expectations of how artifacts should look and behave enhanced aesthetic literacy, or the "conceptual awareness which allows diverse persons to more actively become agents in their environment, combining knowledge, imagination, feeling, and skills" [17].

Supporting sensors in a CWM workflow

Although the scope of the work is focused on actuation, the larger ecology of electronic and hybrid materials face similar challenges. Inverting the formal analysis (Figure 2) yields some starting points for supporting sensors in a conversation with materials workflow. For instance, how might creative environments expose the phenomenology of the sensed stimuli (e.g., from a heartbeat, from the environment), convey the limits of its observation (e.g., single point sample, distributed sensing), or communicate how it was processed and encoded (e.g., thresholding, machine learning). From an interaction design lens, there is additional opportunities for extending the formal properties of triggers to move beyond "if this then that" and occur probabilistically or evolve dynamically.

Curating creative spaces



From this exploration, we see potential trajectories for tangible interfaces to emerging hybrid material practices such as e-textiles or paper electronics. Stages may offer an exploration, testing, and reflection environment custom to the unique challenges and concerns of a practice including organics, biologicals, chemicals. For instance, a paper electronics station for resistive heaters could offer specialized power and control terminals as well as curate and affix a host of different thermoreactive materials to explore heat as a material. For e-textiles, a stage could incorporate more of the physical practice, exposing power and control through a mannequin, in conjunction with electronic tools translated to the textiles domain [37].

CONCLUSION

This work presented the design of a novel, creative workstation to support a "conversation with materials", aiming to expose the different physical and digital material actors present within actuation design. We treated the data signal as a computational material and exposed its distortions, capabilities, and its influence on actuators and space as a creative agent. Through a tangible, networked, and modular interface, we demonstrated the value of distributing creative agency across multiple form factors and of defamiliarizing computational design practices to expand on the aesthetic literacy of hybrid design elements.

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