Playing the Print: MIDI-Based Fabrication Interfaces to Explore and Document Material Behavior

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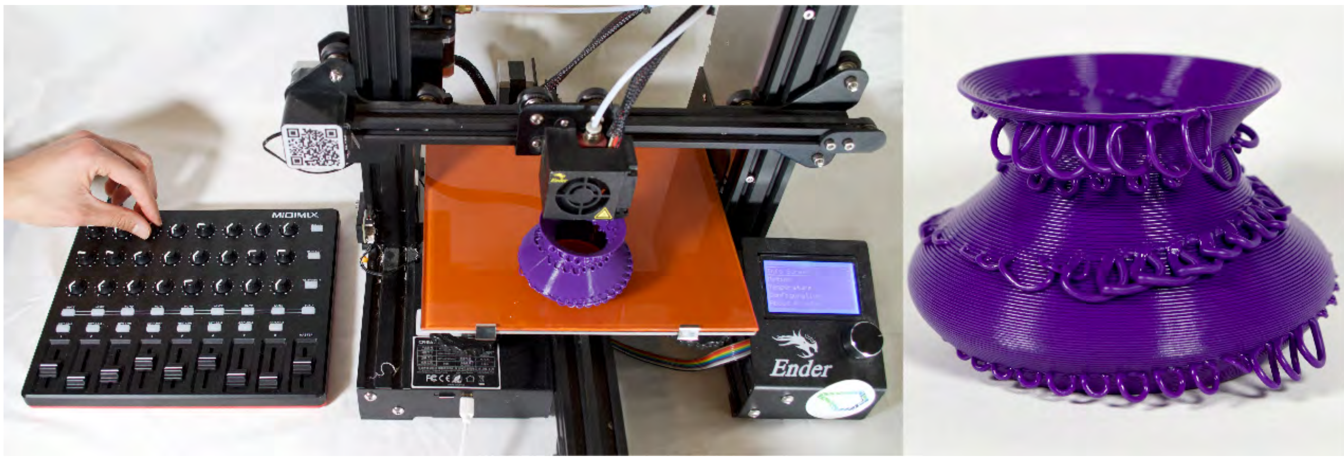

Figure 1: We present MIDI-based fabrication interfaces to explore and document material behavior. On the left, a 3D print is interactively tuned to explore the effect of machine settings on unsupported loop structures. An image of the resulting print is shown on the right. Apparent in the image are loops of a variety of sizes and thicknesses. Our system records machine instructions and MIDI input to be played back in lockstep with video of the fabrication process.

ABSTRACT

Digital fabrication software supports common activities like designing models and setting parameters. However, the increasing diversity of fabrication materials and contexts means that determining the right settings is a constant challenge. Manipulating machine parameters and observing material results is necessary for successful outcomes. In this work, we present tools to iteratively develop computer-controlled fabrication workflows. These tools generate toolpaths using Javascript code, continuously manipulate parameters during machine execution, and document the resulting material behavior. First, we present software to interactively tune 3D prints. We use a MIDI controller to modulate fabrication parameters during execution. We demonstrate our approach through a set of 3D prints created with our software. Second, we introduce software which synchronizes video of a fabrication process with the machine instructions being executed. Doing so archives the effect of manipulating machine parameters. We argue that infrastructure which encourages exploration and documentation of both code and materials are crucial to support broader uptake of fabrication technologies in creative contexts.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

KEYWORDS

Fabrication, 3D printing, p5.js, p5.fab, MIDI control, Creativity, Digital Art, Documentation

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1 INTRODUCTION

As the number of fabrication materials and contexts continue to grow, it has become increasingly critical to support the exploration of machine settings and material output [1, 21, 43]. Any material, from well-understood thermoplastics to experimental biocomposites, has distinct material properties which determine its design space, e.g., [4, 6, 33, 45]. Fully asynchronous design workflows are at odds with open exploration of material behavior [3, 19, 31]. We

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argue instead for interactive control of digital fabrication machines with documentation of the resulting material output.

To help us think through the development of machine interfaces for iterative material exploration, we can productively compare digital fabrication practice with creative coding. Creative coding is broadly the practice of coding for expressive rather than functional purposes. It promotes thinking through programming rather than satisfying predefined specifications [25], and is used by millions in contexts ranging from education to professional art [27, 30]. Subbaraman et al. [37] show how in creative code communities, iterating with parameters is core to their creative practice. We argue that digital fabrication would benefit from tools that support similar exploration and iteration.

When developing alternative maker tools, Bardzell et al. [2] ask: "is it not possible to imagine and work towards sociotechnical ecosystems that better support a holistic project of making makers?" Our goal with this work is not only to overcome a technical limitation in computational fabrication software. Rather, echoing others' goals in systems research for physical production [7, 22, 26], we wish to investigate the potential for a broader ecosystem of maker tools which can support continued development of creative community. This is why we couple interactive control software with integrated video documentation techniques. By documenting both software and material behaviour together, we can archive and share the material insights gained through exploration. We invest in the idea that communities around such tools can support the development of computational and maker knowledge, connect experts across these domains, and nurture variable and varied maker identities.

Towards these goals, in this paper we contribute tools which support interactive exploration of 3D printing parameters and video documentation of material output. In particular, we extend existing open-source software which enables control of digital fabrication machines from the creative coding environment p5.js [35]. We mobilize two distinct metaphors in our interactions with digital fabrication machines: live musical performance and video closed captioning. First, we observe that testing material behaviour often requires time consuming trial-and-error loops. To aid in the exploration of interdependent machine and material settings, we present software to modulate fabrication parameters during execution using a MIDI controller[1]. MIDI controllers are physical input devices used in live music performance to modify parameters and trigger events; they are often a panel of knobs and sliders (see Figure 1 left). We use off-the-shelf MIDI hardware in conjunction with custom 3D printing software to map MIDI messages to fabrication parameters while the machine is running. By using physical hardware rather than software control panels, we aim to productively shift operator attention from screens to machines. Second, we consider the difficulty in documenting the insights gained through material exploration. Dynamic material behavior is not sufficiently captured by machine code or static media alone. The problem of material documentation is compounded by the introduction of our proposed interactive control software. We therefore contribute software which synchronizes video of a fabrication process to the machine code being executed, the source code which generated the machine code, and the MIDI values which have been used to tune machine parameters. By 'captioning' the video with code, we can scrub video, machine code, and source code in lockstep to evaluate the effect of changing parameters. We share our experiences using the system and discuss opportunities and challenges in developing creative maker infrastructure which support exploration and documentation.

[1]MIDI, or Musical Instrument Digital Interface, is a standard that describes a communication protocol, digital interfaces, and electrical connections. Interactions with MIDI keys, knobs, and sliders are recorded as MIDI data, which can be used to control parameters like timing, pitch, and loudness.

2 BACKGROUND & RELATED WORK

Our work builds on current conversations around interactive machine control, material exploration, and physical documentation methods. Where previous interactive systems have highlighted the ability to manipulate the overall form of a fabricated object, we focus on tuning specific machine settings. Doing so helps prioritize material exploration and understanding. We further negotiate the need for clear, shareable documentation of a fabrication process with the messy realities of a material-driven design process. We situate and distinguish our work in this section.

Noting the limitations of a conventional digital fabrication workflow from design through machine execution [43], a growing number of systems have explored alternative approaches. These include appropriating existing slicer software [14], developing custom slicers [38], and directly describing machine toolpaths [15, 16, 18, 32, 35, 39, 40]. The latter are particularly aligned with our goals of iterative material exploration. We hone in on iterative material testing to tie together several threads of current digital fabrication research. For example, recent research has focused on printing materials like clay [3], coffee grounds [33], and Play-Dough [5], none of which have default slicing profiles in off-the-shelf CAM software. Well-understood materials like PLA are also continually being used in new contexts, such as to create foams with graded material properties [11]. Across these disparate fabrication materials and contexts, operators must undergo time-consuming trial-and-error loops to understand how the material will behave. Bourgault et al. [3] call for action-oriented systems which promote conversational feedback loops between operators, machines, and materials. Cultivating a sensitivity to material, they develop a system specifically for clay 3D printing. We are likewise interested in how fabrication interfaces can attune operators to materials. We specifically extend existing programmatic approaches to toolpath design from the creative coding environment p5.js [35] to support interaction while the machine is running.

Other have also pursued interactive fabrication systems which respond to realtime input [47]. However, many systems are most concerned with modulating the overall form of the object, e.g. [28, 46, 49]. Similar to our approach is Compositional 3D Printing [23] which maps multiple design inputs during production. We build on this vision of continuous fabrication interfaces. We distinguish our approach with a focus on machine settings rather than form. Our MIDI interface promotes independent exploration of parameters, an important aspect of fabrication practice [36]. Wu et al. [48] created foot pedals to promote improvisation and embodied interactions with a Jacquard loom. The authors suggest opportunity for more 'playful peripherals' in digital fabrication. Our MIDI interface similarly uses a music-making design metaphor. In particular, we aim for physical hardware to shift operator attention from digital screens to the physical machine, a strategy which has proved useful in designing tutorials for physical skill development [12]. We moreover pair our approach with techniques to document the resulting material behavior.

Documenting fabrication workflows is a difficult and time consuming activity; practitioners often have to choose between making progress on their project and creating documentation [34]. Documentation that is created often focuses on the final product. However, Tseng and Resnick [42] find that most readers of documentation on the website Instructables are interested in customization, not rote recreation. For these users, process-oriented documentation is a more useful resource.

Goveia da Rocha et al. [20] investigate documentation strategies in the context of material-driven design workflows. Their insights shed light on the diversity of ways in which designers make use of material samples. In particular, it is difficult to archive material samples as they are discarded or forgotten about upon project completion. Relevant systems take advantage of visual markers left by the fabrication process to archive slicer parameters [9] or embed tags for later recall [10]. However these approaches are not compatible with exploratory processes which do not use conventional CAM software. In our work, we augment video documentation with synchronized captions of machine instructions. In particular, we record MIDI input and present this information alongside the original toolpath design and final machine code. Doing so creates a form of documentation that can be saved, evaluated, and shared.

3 A LIVE PERFORMANCE APPROACH TO MACHINE CONTROL

To support interactive exploration of fabrication parameters, we adopt a musical performance approach to machine control. In particular, we use physical MIDI controllers as input, mapping MIDI messages to various parameters. Our code is open-source and available online at https://github.com/machineagency/p5.fab. In this section, we motivate this approach and detail our implementation.

3.1 Walkthrough

To motivate our software, consider the following example. Say we would like to 3D print a textured vase. A popular technique to achieve surface texture in 3D printing communities is the use of unsupported 'loops'. These loops are extruded such that the material naturally hangs (see Figure 1 right). The approach is particularly popular in ceramic 3D printing where current hardware mandates continuous deposition; printing loops inverts this technical limitation to instead showcase the material properties of clay [3, 6]. Implementation using traditional computer-aided design and slicer software is not straightforward. Direct CAM-based design, as described in Section 2, is required. Even after a base design is reached, it is difficult to explore the resulting design space. The look and feel of the 3D printed loops are a function of loop shape, loop size, nozzle temperature, printhead speed, extrusion amount, filament material, base geometry, and more. Testing these parameters would typically be accomplished by re-printing the design multiple times. Using

Figure 2: (Top) Exploring loop parameters with our MIDI-interface. Loop radius, extrusion, and speed are varied during execution to understand the material response. (Bottom) After exploring a variety of loop shapes and sizes, we can commit to fabrication with desired parameters. Shown is an image of a print with constant loop settings, determined through previous exploration.

Figure 3: Our approach can be applied in a variety of contexts. In the prints shown, speed, extrusion quantity and toolpath geometry are modified to catalog a variety of woven textures.

our approach, we can intuitively explore inter-related parameters in the following way:

Design the base toolpaths. To begin, we write p5.js code which describes the overall geometry of our object. Specifically, we augment existing examples to print an undulating vase with a `hangingLoop()` function which takes as its arguments a radius, extrusion multiplier, and speed. When called, the function will add a circle on the exterior of our print, tangent to the current layer contour. In our code, we use a custom command to tag this function with the name 'loop'.

Define the MIDI-to-machine mappings. In a separate file, we define the mapping between MIDI controller knobs and fabrication parameters. We use the first available MIDI knob to set a speed between 5 and 50 millimeters per second, the second knob to set an extrusion multiplier value between 0.5 and 5, and a third knob to a set a loop radius value between 2 and 10 millimeters. We then specify the tags to which our values should apply; in this example, we only want our MIDI values to modulate code within our 'loop' tags.

Execute and Modulate Commands. We connect our computer to our 3D printer and MIDI controller using wired USB connections. When we are ready to begin, we start streaming the commands. To start, the machine uses default size, speed, and extrusion values when printing loops. We observe that the loops are printed too quickly and appear as blobs of filament rather than well-defined circles. In response, we slow down the loop print speed using our first MIDI knob and increase the loop radius using our third knob. We then notice that large loops are distorted as the filament clings to the nozzle. We increase the extrusion multiplier, causing the heavier filament to sag down and away from the nozzle, better holding its circular shape. We continue in this manner to experiment with different combinations of parameters (Figure 1 right, Figure 2 left).

3.2 System Overview

Our system extends p5.fab [35] to monitor MIDI messages and modify outgoing commands. We have tested our software using a Creality Ender-3 Pro and an Akai MIDImix control panel[2]. Our approach, however, is broadly compatible with any MIDI controller and printer running Marlin firmware. The software can be adapted to accommodate other G-Code flavors.

3.2.1 MIDI Integration. p5.fab [35] enables control of digital fabrication machines from the browser using p5.js. We build on this open-source software, leveraging WebMIDI support to monitor incoming MIDI messages. MIDI messages specify the ID of the number, slider, or button which has been updated. Slider and knob events are accompanied by a value between 0 and 127. Our software monitors each MIDI value. Operators can assign each MIDI input a relevant name in code (e.g. `printSpeed`) and map the incoming value to a suitable range (e.g. 5 to 50 mm/sec). Button presses trigger MIDI events on depression and release; we can similarly tie button presses to actions (e.g. start streaming command). Finally, we can provide a list of strings, or tags, to specify sections of G-Code to which the MIDI values should be applied.

3.2.2 Interactive Modification. We add each machine instruction generated by our software to a queue to be sent to the machine. For modification during machine execution, we catch instructions before being sent to the printer and update them using current MIDI values. However, instructions related to movement are added to an internal buffer on the printer's control board to plan the machine's motion. Once added to this buffer, we cannot modify the command. As a result, the latest instruction which our software has access to lags an unknown time behind the most recently executed command. Modifications to machine parameters using data from our MIDI controller are therefore significantly delayed. This effect is particularly exaggerated when executing long, slow moves. To achieve a near real-time effect, we subdivide each move command into a series of small, linear moves (1mm by default). We can then modify the latest commands in our queue with values from our MIDI controller. Depending on the current printer speed and the size of commands sent, changes are applied within a second. For greater

[2]https://www.akaipro.com/midimix

responsiveness, or to accommodate very slow moves, commands can be subdivided into smaller segments.

Notably, our approach to subdivide commands into small moves can impact print quality. The printer's motion planner uses commands in the move buffer to coordinate matters like acceleration and deceleration. With smaller moves, the planner has less information to choreograph motion. Our approach therefore may not be suitable for high stakes fabrication contexts. If moving at high speeds with small subdivision lengths, the printer can stutter as there are no commands in the queue to execute; resolving this issue negotiating tuning the subdivision length and print speed. However, in our use of the system, prints with and without subdivision were largely indistinguishable. The benefit of our approach is that no printer modifications are necessary. It is therefore relevant to a large number of machines and practitioners.

3.3 Examples

Figures 1 and 2 present examples of the workflow discussed in Section 3.1. Figure 2 demonstrates how insights gained through MIDI exploration can be used to inform future prints. After exploring multiple loop designs, we decide that we particularly like the appearance of small, thin loops. We can therefore commit to fabrication of a new vase with our tuned values (Figure 2 middle). While we tuned loops as a representative example, we can broadly tie our MIDI control to any parameters expressible in G-Code. For example, Figure 2 (right) shows an in-progress print where speed, extrusion, and deposition height are modified to explore the natural coiling of PLA. In this example, using intuition to respond in real-time to material output offers a clear advantage to asynchronously designing a model which sweeps the relevant parameters.

4 DOCUMENTING MATERIAL OUTPUT WITH VIDEO AND CODE

To support documentation of material output, we caption video of a fabrication process with the machine instructions being executed in a process we call 'fabscription'. We moreover synchronize video playback with the Javascript code which generated the toolpath and live MIDI modifications. Our interface is designed to be used with the code presented in Section 3, and is available at https://github.com/machineagency/fabscription. In this section, we detail our approach.

4.1 Walkthrough

Recall the loop vase which we created using a MIDI controller in 3.1. Some time after our initial exploration, we wish to print a new vase. We particularly like the look of some of the small loops, but we aren't sure what values were used to tune the radius, speed, and extrusion multiplier. Developing new test prints which sweep these parameters would be time consuming. What we'd really like is documentation of our original interactive print which we can refer back to. Using our software, we can document our material explorations in the following way:

Set up a Camera. Before printing our interactive loop design from Section 3.1, we set up a USB webcam pointed at our printer.

Play (and Record) the Print. As before, we define MIDI mappings and interactively tune the print. This time, however, our webcam captures the machine's movement on video. Our software additionally records the MIDI messages over the course of the print. When the print is complete, we save the autogenerated log file and video.

Fabscribe the Print. We open our Fabscription web interface and upload our video and log file. The interface shows the video, machine instructions, Javscript code, and chart of MIDI values (Figure 4). As we play the video, the current machine instruction being executed is highlighted, along with the relevant line of Javascript code which generated this machine instruction. We moreover can see the value of the each MIDI parameter at that timestep. Using the interface, we find where our favorite loop is printed and take note of the relevant values. We can use this information to print another vase. We keep the log file and video for future use.

4.2 System Overview

Extending the same software described in Section 3, we record MIDI messages and machine position data over the course of the print. We then sync video and code in a process which we call 'fabscription'.

4.2.1 Recording MIDI and Position Data. To record MIDI data, we simply log the time and value whenever new messages are received. For position data, we make use of the realtime position option for Marlin firmware. This returns the current position using stepper motor data rather than the next projected position based on G-Code instructions. We modify our streaming functionality to query the position after every sent command and record the value and timestamp. Since new commands are only sent when there is space in the printer buffer, each position we receive will match closely with a line of G-Code. We use this data to match positions and therefore start and end times of each G-Code command. Our software takes into account the printer buffer size to avoid redundant data at the start of the print, and pads the G-Code with an appropriate number of empty move commands so that we continue to receive position data while the buffer is emptied at the end of the print.

4.2.2 Fabscription Interface. Our web interface is shown in Figure 4. The interface shows the recorded video, machine instructions, p5.js code, and a simple visualization of MIDI data. As the video plays, the machine instructions advance in lockstep. Scrubbing forwards or backwards in the video, or selecting a new line of G-Code, will cause the other view to update automatically. We also show the line of the p5.js sketch which generated the relevant line of G-Code. In doing so, we promote sensemaking of the code as well as the material outcome. Finally, we show the MIDI value over time for each configured parameter. Using the visualization, we can determine MIDI values at any timestep.

5 DISCUSSION

Digital fabrication practitioners gain deep material knowledge through their interactions with machines [8]. However, fabrication interfaces often force practitioners to enact this knowledge in roundabout ways [24, 35, 36]. To understand how fabrication interfaces can better support practice, we explicitly support iterative material testing through interactive MIDI-based control. We do not

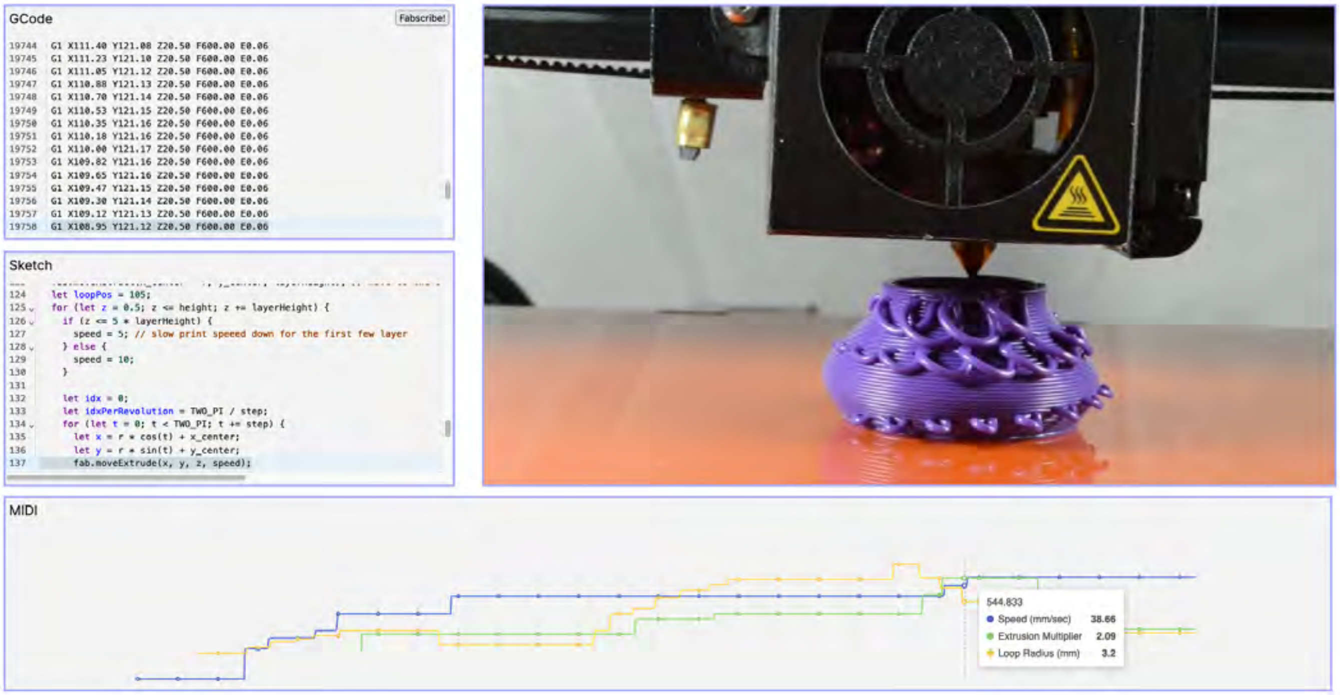

Figure 4: Our web interface synchronizes video of a fabrication process (right) with the machine instruction being executed (upper left). In the example shown, the current video frame is executing the G-Code line highlighted in blue. We also present the line of Javscript code which generated the current machine instruction (middle left), again highlighted in blue. The MIDI values for all variables over the course of the print are presented as a graph (bottom); here we are varying the speed, extrusion, and radius of loops on the exterior of the print.

seek to replicate the functionality of existing computer-aided design and manufacturing software, which is already well optimized for conventional fabrication goals. Instead, our tools support an alternative design space which can be explored in its own right, or used to develop material insights to be applied in future fabrication processes.

Our goals here are two-fold. First, we aim to support individual exploration of materials. By interactively tuning prints, operators can observe and respond to material and machine behavior. This is important not just to facilitate development of material knowledge, but also to enact existing material expertise. Broadening participation in creative system development does not include only novices, but also visual artists [26], glass artists [15], weavers [7], ceramicists [3], and more. Tools for material exploration cut both ways.

Second, we look to incentivize material documentation. Creative practitioners often develop bespoke methods to version control and document their work [34]. The tools presented here can be used to document and archive fabrication processes for future recall. While documentation can be a constructive component of an individual's practice, the resulting insights are difficult to communicate with others. Moreover, it puts the burden of documentation solely on individuals. In addition to supporting individual documentation, we also consider how tools for material documentation can support distributed community. While popular online repositories like Thingiverse distribute slicer and machine settings alongside design files [29], this information is detached from its original material context. Others have usefully augmented Thingiverse data to help users choose parameters based on time and material constraints [13], however this approach relies on the use of conventional CAD and CAM software. On the other hand, creating more robust resources require significant effort [42]. Playful approaches to documenting physical workflows have potential to inform how practitioners relate to and engage in documentation [17, 41]. To develop vibrant creative community around alternative machine control software, we need to be able to develop and share material insights easily.

A key takeaway of the work presented here is to view material exploration and material documentation as necessarily coupled. As we tune various settings with our MIDI interface, we are also generating documentation which can be referred back to and shared. Material output documents code, and code documents material output. The result is not a definitive account of the fabrication process but a more generative starting point to build from. It is unlikely that, even given the same settings, another machine will produce exactly the same vase shown in Figure 1. However, the relationship between interdependent parameters can be communicated through our fabscription interface. In doing so, we aim to encourage an attitude of active exploration over passive replication.

Our work is limited in several ways. As noted previously, a design approach predicated on custom toolpaths is currently best suited to vase-mode objects and shapes that are mathematically describable.

Editing toolpaths during execution risks both the machine and the artifact, and the MIDI controller can become out of sync with the machine (e.g. if the machine is homed after manually adjusting positions with a slider). Applying our approach to larger machines and more sensitive materials requires additional safety considerations. Our software is moreover focused on 3D printers running Marlin firmware. Additional work is required to extend our approach to additional G-Code flavors and machine command sets. While we have motivated the use of our software with other materials such as clay or biocomposites, we have only tested the software with PLA. Future work will investigate how our MIDI interface is used by practitioners from various domains and with various materials. Finally, the workflow described here requires programming knowledge and is therefore not immediately accessible to everyone with a 3D printer. However, digital fabrication workflows often already involve navigating multiple softwares and libraries [44]. The larger vision described in this work aims to develop and connect experts with both computational and maker knowledge. We believe that cross-pollination between these communities can motivate further research contributions and extend fabrication practice.

6 CONCLUSION

We presented MIDI-based fabrication interfaces to explore and document material behavior when using computer-controlled machines. We extend existing creative coding interfaces for machine control to interactively tune 3D prints during execution. We pair our interactive control system with software to record and play back material explorations in lockstep with video documentation of the fabrication process. Doing so supports development of material knowledge while documenting these insights for future recall. To support the uptake of digital fabrication machines in creative contexts, we propose that future interfaces need to consider both exploration and documentation in parallel.

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