Throwing Out Conventions: Reimagining Craft-Centered CNC Tool Design through the Digital Pottery Wheel

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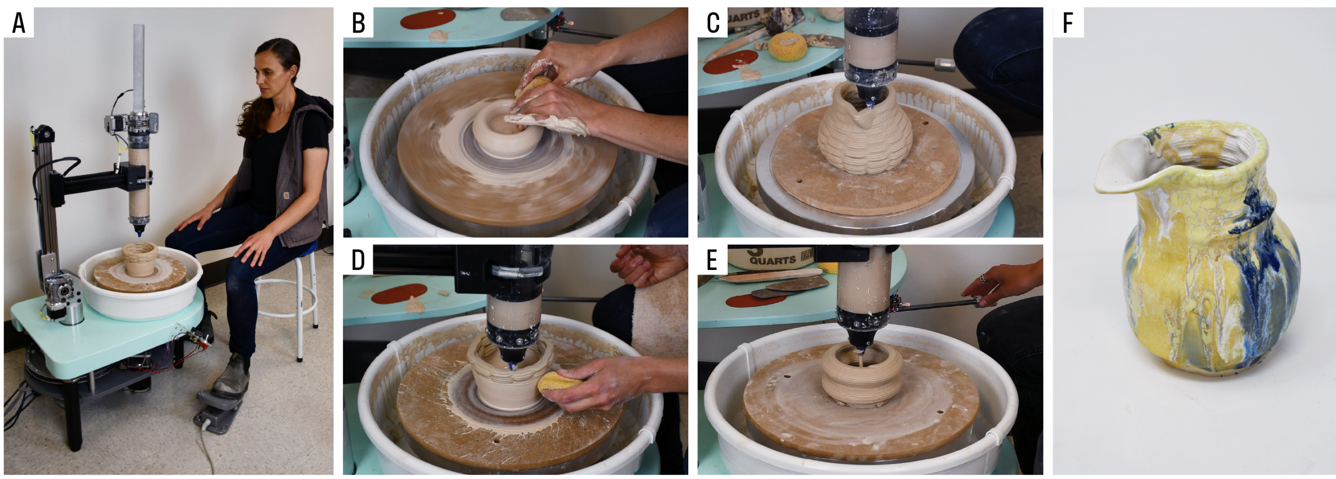

Figure 1: A) The Digital Pottery Wheel (DPW) is a ceramic throwing wheel that is augmented with a polar-coordinate clay 3D printing mechanism and a modular control platform. Through this mechanism and control approach, the wheel supports B) standard manual ceramics throwing, C) GCode-based autonomous 3D printing, D) manual manipulation of printed forms, and E) semi-manual interactive control of 3D printing. F) Here, we show a finished artifact made by artist Isaih Porter on the DPW composed of a hand-thrown bottom, a 3D-printed top, and a manually modified spout.

ABSTRACT

Skilled potters use manual tools with direct material engagement. In contrast, the design of clay 3D printers and workflows reinforces industrial CNC manufacturing conventions. To understand how digital fabrication can serve skilled craft practitioners, we ask: how might clay 3D printing function if it had evolved from traditional pottery tools? To examine this question, we created the Digital Pottery Wheel (DPW), a throwing wheel with 3D printing capabilities. The DPW consists of a polar mechanical architecture that looks and functions like a pottery wheel while supporting 3D printing and a real-time modular control system that blends automated and manual control. We worked with ceramicists to develop interactions that include printing onto thrown forms, throwing to manipulate printed forms, and integrating manual control, recording, and playback to re-execute manually produced forms. We demonstrate how using a physical metaphor to guide digital fabrication machine design results in new products, workflows, and perceptions.

CCS CONCEPTS

• **Human-centered computing** → **Interaction devices**; *Interaction design process and methods.*

KEYWORDS

digital fabrication, hardware prototyping, clay 3D printing, craft

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1 INTRODUCTION

The audience for digital fabrication has broadened significantly in the past 30 years: CNC milling and 3D printing, once restricted to industrial settings, have become widely available to individuals. For some proponents of digital fabrication, this shift suggests the potential to empower a broad audience to design and make anything [3], regardless of skill or experience. This envisioned future has led to research agendas focusing on "personal fabrication" wherein researchers aim to abstract and simplify the processes of designing and fabricating and draw metaphors to fully automated or digital modes of production like the Star Trek replicator [26] and desktop publishing [5]. In contrast, we wonder: *how might digital fabrication best serve those already highly skilled at their craft?*

When examining commercial efforts to develop digital fabrication tools for craft applications, we observe that many of these machines reinforce the conventions of industrial CNC machines and workflows [38, 49, 70, 86]. This trend is especially apparent with the introduction of *clay 3D printers*. Manual ceramic artists build forms by hand or throw them on a pottery wheel [68], and technical knowledge is developed and expressed through touch [50]. Clay 3D printers use the same materials as manual potters. In form and function, however, clay 3D printers have more in common with industrial CNC machines than pottery tools because developers have transposed the apparatus of plastic 3D printing almost verbatim in clay 3D printing technologies [81]. Most of the clay 3D printers on the market today are variants of popular fused-deposition modeling (FDM) machine architectures coupled to domain-specific end effectors [21, 28, 56, 85]. These products also enforce industrial toolchains and interaction models by reproducing the form factor and control method of plastic-3D-printer-as-automated-robot.

Although there are benefits to established 3D printing machine architectures and workflows, re-applying industrial conventions for novel digital fabrication technologies can lead to pushing design patterns in situations where they may not fit [73]. Preliminary HCI research has shown that while clay 3D printing appeals to some ceramics practitioners, the unfamiliar technological paradigm can create barriers to adoption [7, 31]. Moreover, re-tooling industrial CNC workflows for non-industrial settings can lead digital fabrication researchers to solve technical and conceptual challenges that are removed from the values and challenges of independent designers and craftspeople [30]. These findings parallel Ingold's critique of *hylomorphic* conceptions of making where design is conceived as separate from and elevated above material interaction [34]. We build on Ingold's premise to argue that much of CNC engineering constitutes *hylomorphic machine design* wherein both craft skill sets and entire craft fields are implicitly [65] or explicitly [6] are disregarded in favor of CNC and computing norms.

In an effort to eschew hylomorphic machine design and prioritize craft and material practices in CNC machine development, we start by imagining an alternative reality in which clay 3D printing grew out of the physical tools inherent to manual pottery fabrication. We use this premise to pose the following research questions:

- **(R1)** What physical form and mechanical architecture might a clay 3D printer take to reflect the conventions of ceramics tools rather than CNC machines?
- **(R2)** How might professional ceramic artists perceive a clay 3D printer that looks and feels like manual tool?
- **(R3)** What alternative practices and products might emerge from the adjacency of manual and digital ceramic mechanisms in a single tool?

To examine these questions through a practical lens, we engineered the *Digital Pottery Wheel* (DPW): a ceramics pottery wheel with clay 3D printing capabilities. The wheel is an ancient technology with widespread contemporary use [68]. A craftsperson uses a wheel by throwing a piece of wet clay on the wheel, and they manually shape the material into a vessel as the wheel rotates. To anchor our work in existing practice, we used the pottery wheel as a *physical metaphor* to guide our design process. We informed engineering decisions with the ethos that we were building a pottery wheel first and a 3D printer second. We prioritized the form factor of the wheel over established CNC mechanical design precedents that optimize the machine and reduce cost. Our approach parallels the early digital user interface development methodology at Xerox PARC wherein researchers first established the user conceptual model before developing any computing hardware and software [72]. Our development process resulted in two interdependent components. First, we developed a *mechanical architecture* that could be packaged to look and feel like a pottery wheel and support traditional wheel throwing and 3D printing. Second, we developed a real-time modular *control system* inspired by modular synthesizers to enable rapid iteration on automated, manual, and integrated forms of operation.

The DPW mechanical architecture consists of a polar coordinate positioning mechanism for the 3D printer that leverages the rotation of the pottery wheel for angular positioning, with a swinging arm mounted behind the wheel to provide radial positioning of a clay extruder. The component can also move up and down along its rotational axis to provide height variations to the extruder. When the wheel and the 3D printer actions are combined, one revolution of the wheel results in one 3D-printed layer. The radial shape of that layer is determined by the arm's position from the center of the wheel during that revolution. The DPW control system consists of a sequence of printed-circuit board (PCB) control modules that combine and transform motion streams comprised of step and direction pulse trains to control the wheel rotation, the arm rotation, the extruder height, and the extrusion rate. Each DPW module can generate these motion streams based on human inputs, such as hand levers, foot pedals, and pre-programmed G-code files. We developed the DPW control system as a modular structure because it allowed us to rapidly iterate on interactions and creatively layer them together in response to our design process. This process also provided ideological and technical distance from incumbent control paradigms to critically evaluate the role that technologies such as G-code might play in practitioner-driven CNC workflows. Although DPW diverges from conventional 3D printing technologies, we still refer to the tool as a 3D printer. We do so in a deliberate effort to expand the definition of what can and should constitute present and future digital additive fabrication technologies.

We invited nine professional ceramicists to interact with the DPW and create preliminary ceramic artifacts. In parallel, we used their feedback and our observations to iterate on the interaction modalities of the tool. This study provided preliminary evidence that a polar CNC coordinate system aligns with the existing skills and workflows of experienced potters. Furthermore, our study revealed the opportunity for new craft techniques that fluidly alternate between throwing and 3D printing.

We make the following contributions:

(1) A polar-based mechanical architecture for clay 3D printing that supports throwing and 3D printing on the same tool.
(2) A CNC control system that is real-time, extensible, and supports automated 3D printing, manual control, and integrations of both 3D printing and manual control.
(3) The discovery of new interactions and techniques for clay 3D printing elicited through engagement with professional ceramicists with this new architecture.
(4) A methodology that re-centers digital fabrication around skilled craft practice by starting from a craft technology form factor to develop compatible architectures, control mechanisms, and novel interaction paradigms.

2 BACKGROUND

We describe the relationship between CNC and manual craft. We then distinguish the DPW from existing 3D printers and prior interactive fabrication and digital ceramics research.

2.1 Historical and Contemporary Tensions between CNC and Manual Craft

We informed the DPW design ethos by examining trends and alternative paradigms over the history of industrial CNC development. In this section, we describe how these trends shaped the process of working with digital fabrication and the power relationships and perceptions between different kinds of digital fabrication stakeholders. In CNC, an instruction program is made using computer-based tools and fed into a servo-driven machine to control its movement [26]. CNC became dominant early in digital fabrication development. An alternative to CNC was "record-playback" wherein a machinist would operate their tool while a recording device registered their movement. The recording could be played back to reproduce parts [51, p. 84]. Noble argues that in opting for CNC over record playback, machine designers deliberately relocated machine control from skilled operators to specialized engineering departments. As the applications and audiences for digital fabrication have broadened, CNC operation remains largely unchanged from its industrial origins. For nearly all forms of CNC machine interaction, the creator uploads a series of toolpath instructions and either waits until they are executed or responds to an error [79]. This workflow has advantages, but it is in tension with manual craft. CNC workflows restrict design activity to the digital domain– commonly in CAD [25]. Furthermore, CNC prioritizes optimizing cost and performance [51] over material workmanship and direct tool control [62].

This workflow has created repercussions for digital fabrication practices. The CNC paradigm has perpetuated power imbalances between digital and material forms of labor. Noble documents managerial beliefs that CNC machines could be "run by monkeys" despite the substantial skill required [51] and Retelny *et al.* showed that digital designers use CAD to enact power over other practioners [65]. The degree to which digital fabrication growth has impacted commercial production is unclear; however, recent work suggests that existing digital fabrication tools pose limitations for professionals. Hirsch *et al.* showed that independent designers rely extensively on low-level machine control and material knowledge to design and manufacture commercial products [30]. Song *et al.* revealed that manual craftspeople feel that digital fabrication tools are not mature enough to advance their productivity and creativity [73]. Despite the benefits of automated CNC in some industrial settings, we argue more automated computer-based design tools for digital fabrication will not necessarily lead to greater adoption by skilled manual professionals. In fact, such tools may *disempower* professionals in some cases.

2.2 Conventional and Craft-aligned CNC Mechanisms

When designing the DPW, we developed a new printer architecture and control paradigm to support manual throwing. To illustrate the differences between our approach and existing 3D printers, we describe the primary mechanisms used in current commercial additive fabrication technologies.

2.2.1 Commercial 3D Printer Mechanisms. Almost all commercial 3D printers are automated output devices for CAD models [32]. This automated workflow has shaped 3D printer mechanical architecture. A central mechanical challenge for FDM printer design involves reducing moving mass [27]. Engineers have maximized performance through low-inertia parallel kinematic positioning mechanisms. Many 3D printers [11, 61] use Cartesian mechanisms, which involve configurations of rectilinear axes [2]. Other popular architectures use variations of pulley-based [45, 80] and non-rectilinear mechanisms [64]. Regardless of mechanism, all commercial 3D printers we are aware of, including one polar mechanism [59], use Cartesian coordinates [2], meaning that position is specified in X, Y, and Z coordinates. We refer to 3D printers that use linear motion mechanisms, rectilinear or otherwise, *and* Cartesian coordinates as *Cartesian 3D printers.* Compared to commercial printers, the DPW is unique because we use a polar mechanism *and* coordinates.

2.2.2 Interactive Fabrication. Although the majority of commercial 3D printers are automated Cartesian devices, HCI researchers have investigated alternative CNC mechanisms and interactions that introduce new architectures and interaction modalities

The DPW integrates real-time control of machine fabrication. Our work intersects with the broader domain of interactive fabrication [87]– a widely explored topic with HCI. Mittenberger *et al.* use motion tracking to translate human gestures to a robotic plastering system [44]. Albaugh *et al.* augment a knitting machine with sensing and machine-state feedback [1]. Tian *et al.* constrain power tools through shared robotic control [75]. To our knowledge, the DPW is the first interactive clay 3D printer. Our efforts align with prior work to integrate skilled subtractive fabrication with digital control. Rivers *et al.* use computer vision and an actuated linkage to precisely position the cutting bit of a hand-held milling tool [66]. Turn-by-Wire augments a CNC lathe with force-feedback hand wheels to provide haptic feedback [76]. Matchsticks supports

Figure 2: Hand-built, wheel-thrown, and digitally fabricated ceramics reflect different qualities depending on the practitioner's technique. A) Hand-coiled lighting vessel by Pilar Wiley. B) Wheel-thrown pitcher with hand-pulled handles by Isaih Porter. C) Thrown vessels with luster glazing and manual surface ornamentation by James and Linda Haggerty. D) Hand-coiled moon jars with crawl-glaze surface features by Raina Lee. E) Hand-built sculpture created using CNC press molds by Del Harrow. F) Lower portion of the hand-coiled vase with nested clay 3D printed miniature by Eun-Ha Paek. G) Auger-extruder Clay 3D printed sculpture by Joey Watson. H) Clay 3D printed Poodle also by Eun-Ha Paek. I) Detail of mixed thermoplastic and clay 3D printed sculpture by Lynda Weinman.

joinery through an interactive fixturing workflow for successive cuts [77]. Our approach is most similar to Turn-by-Wire. A pottery wheel is similar to a lathe's rotational aspect; however, we focus on additive fabrication and support direct material engagement.

To preserve manual interaction in digital fabrication, researchers have also digitally augmented hand-held tools. The Digital Airbrush [69] and the FreeD [93] enable computer control of an airbrush and Dremel tool, respectively. DCoil supports 3D wax coiling through a position-correcting extruder [55]. RoboSketch blends a robotic ink printer with a stylus [58]. Haptic Intelligensia guides a hot glue gun through a Falcon Haptic controller [39]. Muscle Plotter uses Anoto tracking and EMS to guide manual drawing [42]. DePENd guides drawing through an actuated magnet [88]. We differentiate our work from augmented manual tools that aim to reduce risk or compensate for a lack of manual skill through automated position correcting or mechanical guidance. Instead, we augment the existing skills of experienced manual potters through an additional fabrication modality.

Researchers frequently use augmented reality to guide interactive and manual-digital fabrication control systems. The Constructable guides laser cutting using a projector and laser pointers to denote cutting actions [46]. Hattab and Taubin guide rough carving by projecting computationally determined steps onto stock [29]. RoMA uses mixed reality to couple digital design with 3D printing [54]. Being the Machine subverts 3D printing by allowing designers to execute material-agnostic additive fabrication actions with the guidance of a G-code driven laser [17]. In its current iteration, the DPW lacks any form of augmented reality guidance because our primary focus was on mechanism and control system design. We see future opportunities to use digital feedback on the DPW to guide artists' manual interaction with material in a manner similar to Devendorf and Ryokai.

2.2.3 Modular Digital Fabrication Machine Architectures. By combining a clay extruder and wheel through a modular control system, our research contributes to developing modular and extensible digital fabrication machine architectures. Examples include Popfab, a CNC with a suitcase form factor and interchangeable end effectors [53], Jubilee, an open-source machine with automatic tool changing [82], and the Cardboard Machine Kit, a modular motion platform system for CNC design [52]. In recognition of the challenges conventional CNC control systems present for experimental and extensible CNC development, Read *et al.* developed a method for operating on and synchronizing multiple machine component trajectories [63]. Our control system similarly manipulates the trajectories of DPW's axes but does so in real-time on step and direction streams rather than buffered abstract representations.

2.3 Ceramics and Digital Fabrication

The DPW builds on prior research in clay 3D printing, a form of digital fabrication dependent on and closely integrated with traditional ceramic research and production. The Unfold Design Studio developed out-of-the-bag clay 3D printing in 2009 [81]. Developers have since created a range of commercial clay 3D printers with varying end-effectors [21, 56, 83]. All commercial clay 3D printers use Cartesian coordinate systems and most use rectilinear architectures. The two exceptions are the Delta-based Wasp [85] and the Potterbot Scara which rotates along two linkages [57]. We contribute a novel polar clay 3D printing mechanical architecture; however, we repurpose a PotterBot extruder and Z axis in our design.

Clay 3D printing supports different qualities from wheel throwing and hand building. Still, it is difficult to reproduce the expressive range of skilled manual ceramics with 3D printing alone [36] because 3D-printed ceramics comprise wet, unsupported, and uncompressed coils. Figure 2 shows a range of manual and 3D-printed ceramic works. Clay 3D printing requires similar material knowledge to manual ceramics [14], and practitioners frequently integrate hand work and 3D printing [7]. In creating the DPW we were inspired by the reality of clay 3D printing as a manual and material practice. Artists and craftspeople have contributed extensively to clay 3D printing research. Our work was informed by Keep [37] and Simpson [71] who engineer their own 3D printers; and Brady [8], Tihanyi [78], and Foran and Suon [22] who developed novel computational design methods.

Within HCI, we are not alone in drawing design inspiration from the field of ceramics. Clay and ceramics production has long been a site of inquiry and inspiration for HCI researchers. The Sound Bowl explores the tensions between ceramics and laser cutting [67]. Hybrid Reassemblage uses the reconstruction of slip-cast vessels with 3D printed parts to challenge digital reproducability [92]. Desjardins et. al. [14] and Zheng et. al. [90] developed techniques for integrating ceramics and electronic sensing. Dick *et al.* use laser engraving to create precise crackle glaze patterns [18] and Horn *et al.* use computational slab building to investigate how digital tools alter craft practices [31]. Despite the trend in HCI research for exploring ceramic production, HCI clay 3D printing research is rare but growing. Desjardins and Tihanyi use CAM-based porcelain printing as a case for domestic data visualization [13]. Buechley and Ta developed a method for precise clay and Playdough composite printing [9]. Within the domain of software design technologies, Bourgault *et al.* developed a toolpath-based programming system for clay 3D printing [7]. Frost *et al.* created an alternative to numerical clay 3D printing toolpath specification with SketchPath [24]– a drawing-based CAM design tool that supports the creation of hand-drawn toolpaths. Friedman-Gerlicz *et al.* developed a clay-specific slicer that enables variable wall thickness [23]. We contribute a novel clay 3D printer to this burgeoning area of HCI. We build on prior methods for clay-specific toolpathing by adapting CoilCAM as our primary digital design method for DPW G-code toolpaths.

3 DPW DESIGN AND IMPLEMENTATION

The DPW consists of a polar coordinate mechanical architecture (Figure 3), which we designed first, and a modular control system (Figure 5), which we designed after establishing our mechanical constraints. We informed our mechanical design through three design goals that targeted [R1]:

- **Preserve pottery wheel appearance:** Potters should see similarities with tools they are familiar with.
- **Maintain pottery wheel functionality:** Potters should be able to achieve outcomes similar to a standard pottery wheel.
- **Maintain 3D printing capabilities:** The DPW should support 3D printing at parity with comparable Cartesian clay 3D printers.

The DPW development team consisted of researchers with mechanical engineering and clay 3D printing expertise, but we lacked manual throwing expertise. We benefited from the fact that we developed the DPW within a craft-research residency with craft professionals. We used this context to conduct a study with professional ceramicists to develop the DPW interaction design. We detail the study methodology in section 5.1. The study also drove the engineering of the DPW control system because we intended it to support the exploration of different interaction modalities. We established two control system design goals that target [R3] by facilitating participatory design with professionals:

- **Encourage iteration:** The design team should be able to quickly and playfully prototype new interactions.
- **Support multiple forms of control:** The system should enable real-time, manual, and automated forms of operation to support fabrication interactions that bridge traditional and digital clay techniques.

Our approach builds on research through design [91] and participatory design [48] in that we use artifacts as design exemplars and benefit from the technical knowledge of craftspeople [15]. Our approach is novel in CNC engineering research in that we develop the mechanical apparatus of the machine *first* and use these physical constraints as guardrails for participatory interaction design and engineering.

3.1 DPW Mechanical Architecture and Construction

To preserve the look and functionality of a wheel, we developed the DPW mechanism as a polar positioning system built around the wheel. The position of the extruder is relative to the print bed and is controlled by angular and radial movements in polar space (Figure 3: θ, R). The pottery wheel circular throwing platform, known as a *wheelhead*, simultaneously serves as a wheel, build platform, and angular positioning mechanism. We repurpose a standard 14" diameter aluminum Shimpo VL Whisper pottery wheelhead (Figures 3A and 4A). We support the wheelhead radially and axially by preloaded angular contact bearings Figures 4C and B). Clay is deposited onto the wheel by a piston *extruder* repurposed from a PotterBot Micro 10 [56] (Figure 3D). We chose the Potterbot extruder because it is compatible with low-moisture clay suitable for throwing. We cantilever the extruder over the wheel with a horizontal *swing arm* (Figure 3B), which, in turn, is mounted to the carriage of a vertical *Z-axis* behind the wheel (Figures 3C and 4F). Radial positioning is achieved by rotating the Z-axis column, which causes the extruder to sweep at the end of the swing arm. This rotation is constrained by a set of preloaded angular contact bearings (Figure 4D). We chose the swing arm because it offered advantages in form and functionality. In terms of form, the swing arm helps to preserve the form factor of a wheel. Compared to a linear mechanism, it requires less space behind the wheel and permits unobstructed throwing by swinging the extruder out of the way. In terms of function, the swing arm mechanism is back-drivable when unpowered, which provides an advantage for safety and convenience because the artist can move it manually. The swing arm offers further functional benefits for moving between extrusion and manual throwing of cylindrical vessels when paired with our real-time control system and physical user interface. We describe these benefits in greater detail in section 4.

We structurally support the DPW mechanism with two parallel 3/8" laser-cut aluminum plates that sandwich the wheelhead

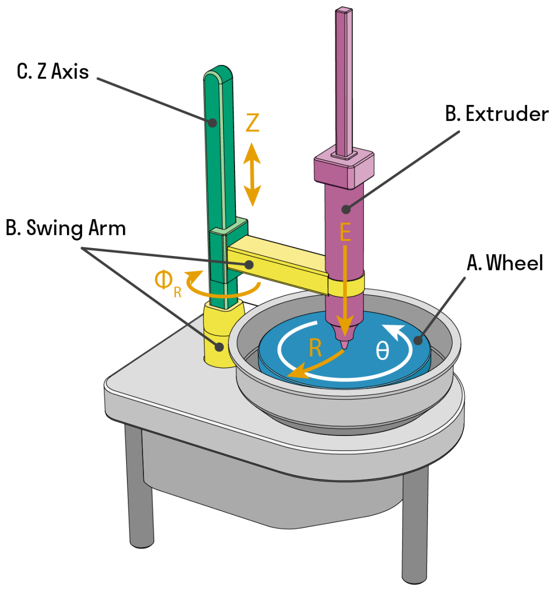

Figure 3: The DPW schematics. A) The wheel component of the DPW rotates around its center with rotation angle θ. B) The swing arm of the DPW rotates around its vertical Z-axis column with rotation angle Φ_R. The arc traced by the cantilever extremity is labeled R, as it approximately corresponds to the radial coordinate of an artifact printed on the wheelhead. C) The swing arm is attached by a carriage on the Z-axis column and cantilevered over the wheel. The carriage can move up and down along that vertical Z-axis. D) The repurposed extruder from a 3D PotterBot Micro 10 is attached to the swing arm, and its piston extrudes clay downward towards the wheelhead.

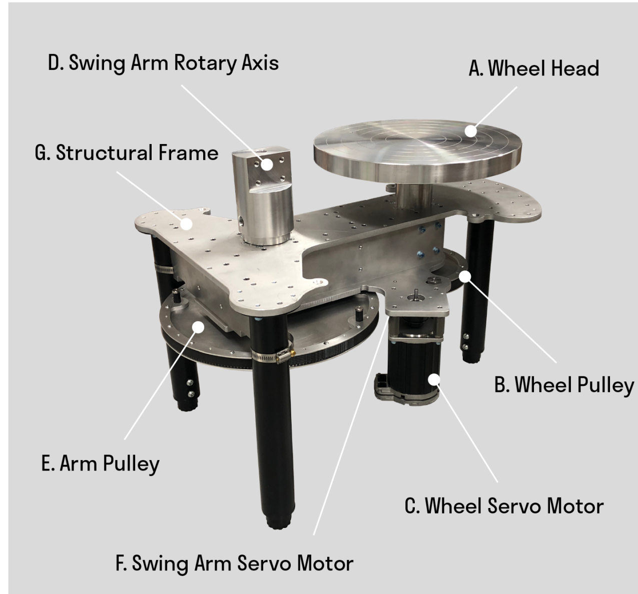

Figure 4: The DPW mechanism. A) A standard 14" diameter aluminum Shimpo VL Whisper pottery wheelhead. The wheelhead is driven by B) a pulley system composed of a 5.5:1 reduction timing belt attached to C) a 400W (1.1kW peak) Teknic ClearPath DC servo motor. D) The print arm rotary axis is driven by E) a pulley system composed of a 10:1 reduction belt connected to F) a 250W Teknic Clearpath DC servo motor (not visible in the picture but directly behind the wheel servo motor). G) These components are fixed on a 3/8" thick laser-cut aluminum structural frame.

and swing arm bearing assemblies (Figure 4G). We suspended motors and transmission elements beneath this frame. We covered the frame with a painted plywood deck and splash pan to protect against clay and moisture.

The total cost in parts for the DPW prototype was approximately $12,500, although this does not account for fabrication and assembly labor. At the time of publication, a Potterbot Micro with an identical extruder volume costs $3,499. A high-end Shimpo throwing wheel costs between $1,500-$1,800.[1]

3.2 Mechanical Performance Considerations and Transmission Specification

To achieve parity with clay 3D printers, we defined three performance targets, drawn from our clay 3D printing experience and the Potterbot specifications: 1) a maximum linear velocity of 200 mm/sec, 2) a maximum acceleration of 5 m/s^2, and 3) a positioning resolution of 0.05 mm. We surveyed commercial pottery wheels and defined two additional targets to maintain pottery wheel parity: 1) a maximum wheel speed of 250 RPM and 2) mechanical output power of 0.5 HP (370 W). With the machine architecture determined mainly by perceptual and usability considerations, our primary levers to achieve our performance targets were the appropriate selection of motors and transmission elements. We used Teknic Clearpath DC servo motors because they are closed-loop and high power density. We exclusively use timing belts for motion transmission because they are quiet, have low backlash, and are backdrivable. The belts couple the motors to the wheel and swing arm and provide mechanical reduction.

Polar 3D printer mechanisms are rare. We suspect this is due to the nonlinearity introduced by the rotational axis, which impacts effective inertia and thus dynamic performance. In Cartesian printers, the transmission ratio–the relationship between the rotational speed of an axis drive motor and its linear velocity– is constant and set by timing belt pulleys or leadscrews. For the DPW, the required rotational speed of the wheel to achieve a particular tangential linear velocity varies with the radial position of the extruder. At the wheel periphery ($R = 180\ mm$), our maximum tangential linear velocity of 200 mm/sec requires a rotational speed of about 11 RPM. Achieving the same velocity near the center of the wheel, e.g., ($R = 8\ mm$), requires 240 RPM (a 22x increase). Because the energy stored in the wheel has a quadratic relationship with its

[1]These values provide data points on initial parts cost in relation to comparable technologies; however, they should not be taken as a direct comparison because the DPW is a prototype and the Potterbot and Shimpo wheels are commercial products.

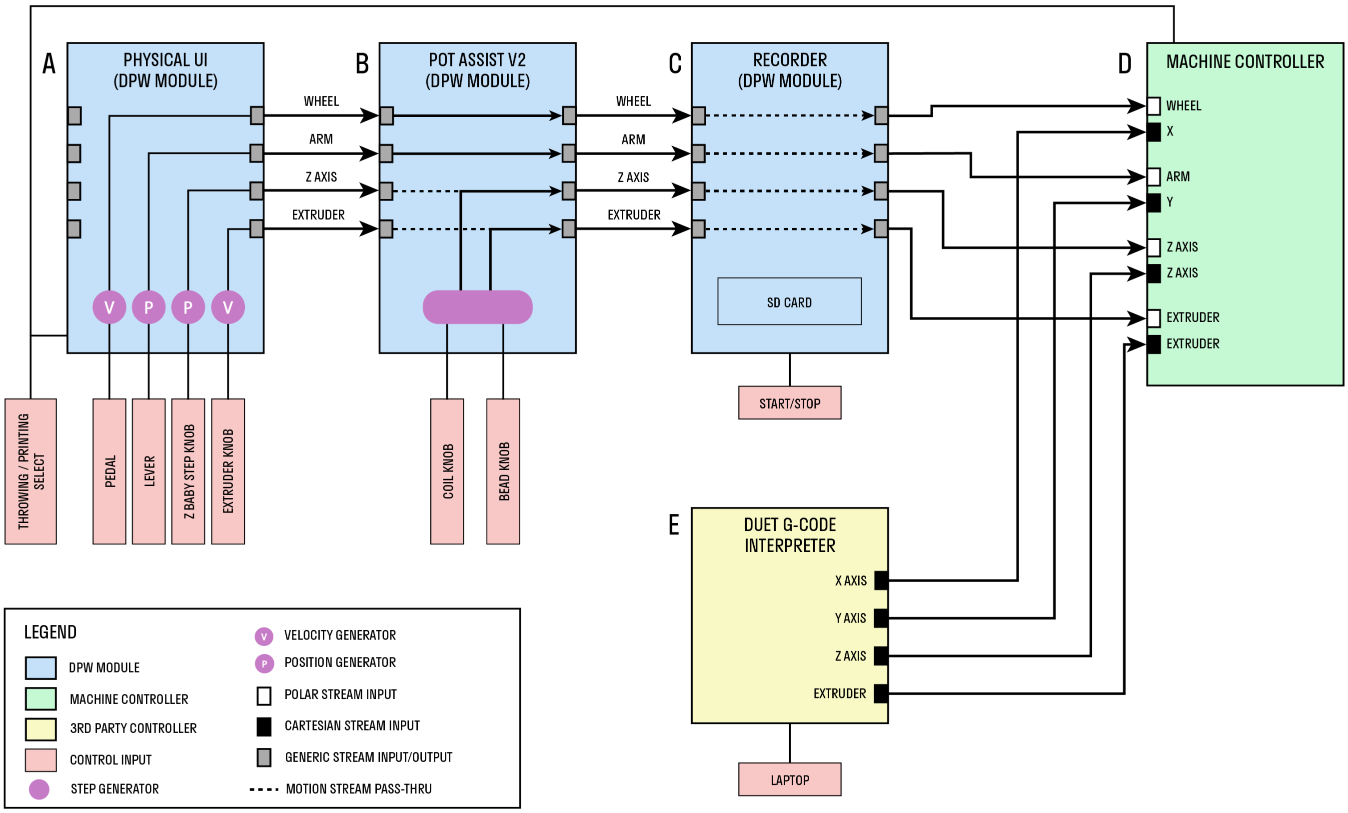

Figure 5: The DPW control system schematic. A) The Physical UI module supports five input peripherals: the throwing/printing select switch, the pedal, the hand lever, the Z baby step knob, and the extruder knob. These last four inputs are mapped respectively to the velocity of the wheel, the position of the swing arm, the position of the Z axis, and the extrusion rate. The stream outputs of the Physical UI module are connected to the stream inputs of B) the Pot Assist V2 module. This module also receives inputs from the coil and bead knob. The stream outputs of the Pot Assist V2 module are connected to the stream inputs of C) the Recorder module. The physical interface on the board enables the artist to start, stop, and playback the recording. The stream outputs of the Recorder module are connected to the stream inputs of D) the Machine Controller. The Machine Controller connects to the machine components illustrated in Figure 3. The Machine Controller also receives inputs from E) the Duet G-code Interpreter, which can relay G-code information from a computer to the DPW control system.

rotational velocity, the effective inertia of the wheel varies dramatically depending on the radial position of the extruder. Accelerating tangentially at a radius of 8 mm from the wheel center requires not 22x but around 500x the amount of mechanical power it takes to achieve the same linear acceleration at the wheel periphery, holding the linear speed constant. Regarding motor performance, we estimated that while only about 2 W of mechanical power could meet our performance objectives at the periphery, 1.1 kW is required at a radius of 8 mm from the center. We use a NEMA 34-sized motor with an output power of 400 W continuous and 1.1 kW peak output for the wheelhead motion to meet our wheel throwing targets. We chose a transmission ratio of 5.5:1 to optimize power output at our top speed of 250RPM.

The DPW swing arm also exhibits high rotational inertia because the filled extruder weighs about 6 kg and swings on the end of a 300 mm arm. The highest achievable reduction ratio that would fit into the DPW form-factor was 10:1. This ratio resulted in a rotational inertia of the swing arm that was 20x that of the motor, and inefficient power coupling between the motor and the extruder. We, therefore, chose the largest available Teknic Clearpath DC servo motor that would allow us to extract the most power under our operating conditions (e.g., 200 mm/s tangential velocity) and transmission ratio.

3.3 DPW Control System

We designed the DPW control system as a series of modules that support real-time, automated, and manual operation. Our control system differs from that of 3D printers. Traditional printer stepper or servo motors are driven by CNC controllers [20, 35] that convert G-code commands into a synchronous stream of step and direction pulses. A microseconds-long pulse on the step line causes the motor to take a step, while the concurrent state of the direction line determines whether the step is forward or reverse. This signaling scheme is powerful because it contains real-time information about each motor's position, velocity, and acceleration; however, G-code controllers do not expose these signals as data. Inspired by modular audio synthesizers, we re-conceptualized these signals as synchronous motion streams. We designed the DPW control system as a series of modules capable of transmitting and modifying these streams as first-class data (Figure 5). We based all modules on the Teensy 4.1 [60]. We use 3.5 mm audio cables as the interconnect between modules. The audio cables transmit +5 V, STEP, DIRECTION, and GND. The power transmitted over the cables is sufficient to power all modules from a single 5 V source. All modules have a small OLED display and RGB encoder knob for configuration and readout. We use a centralized *machine controller module* to maintain state (Figure 5D) and interchangeable *DPW modules* that can be chained together for different composable behaviors (Figure 5A-C).

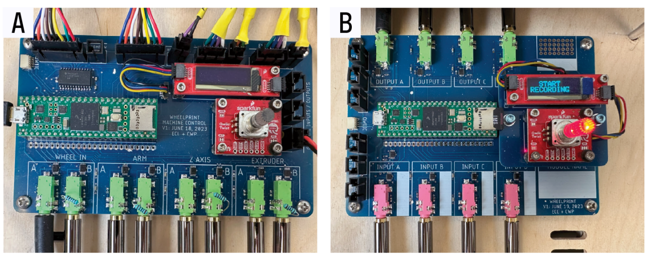

Figure 6: The DPW modules. A) The Machine Controller and B) one of the DPW modules (Recorder).

3.3.1 Machine Controller Module. Step-direction motion signals carry real-time motion information in a relative rather than absolute manner. When following a predetermined path (e.g., when working with G-code), the CNC machine must start at a known position that matches the state assumed by the controller. We, therefore, created one specialized module that maintains the state of the DPW by assuming centralized control over the motors and limit switches (Figure 5D and Figure 6A). When the DPW starts up, this *machine controller* homes the DPW's wheelhead, arm, and Z-axis to known starting positions. Control then transfers over to motion signal inputs from other modules. The machine control module enforces state-preserving velocity and travel limits to minimize mechanical crashes. The machine controller has four banks of motion stream inputs with two channels each. The left channel controls the axes of the machine in native polar coordinates. The right channel supports Cartesian input to maintain the ability to parse standard G-code. The machine controller converts motion stream inputs to these channels from Cartesian to polar space on the fly. We attach these Cartesian inputs to the step and direction pins of four drivers of the Duet3 6XD [19] — corresponding to simulated x,y,z axes of a Cartesian printer, and the actual extruder of the DPW (Figure 5E).

3.3.2 DPW Modules. To enable flexible and composable interaction prototyping, we designed chainable modular PCBs (Figure 6B). Each *DPW module* has four motion stream inputs and four motion stream outputs. They have additional interconnects for up to five analog or digital inputs (primarily for buttons and potentiometers), an optical quadrature encoder input, and a small prototyping area. We created a firmware framework for the modules with various functions that can be modified and combined to implement specific module behavior. We centralized the framework around an interrupt-driven, multi-channel step generator. Every channel has a current position, a target position, and a velocity limit. At each cycle of a 200 kHz timer-based interrupt routine, the channel's current position is compared to the target. If they differ, and enough time has elapsed since the prior step to remain under the velocity limit, a step is generated on an output stream. We implemented a velocity-based step generator that creates a continuous stream of step pulses at a controlled rate. A second function listens to the input signal and directly passes inputs to the step generator channels by updating their target positions or routes them to other parts of the DPW module's firmware to be acted upon.

Our firmware enables us to flexibly mix multiple motion streams, whether they are internally generated (e.g., by a velocity-based generator) or sourced externally (e.g., through a knob or a pedal). We accomplish this by allowing each source to independently update the target position of a common output channel. As a result, modules can pass motion streams through from input to output while layering in additional behavior. Figure 5 shows the current configuration of the machine controller and DPW modules.

4 INTERACTION MODALITIES

We used the DPW control system to prototype multiple interaction modalities. We categorize these modalities across two primary modes: *throwing* and *printing*. We created a *physical user interface* to facilitate tool control and enable switching between modes. The interactions were initially informed by the authors' experience with clay 3D printing and interactions in the craft residency. Following a pilot study with collaborators in an aligning residency, we developed the first iteration of our interaction modalities. We performed further iterations during our formal artist study (section 5.1).

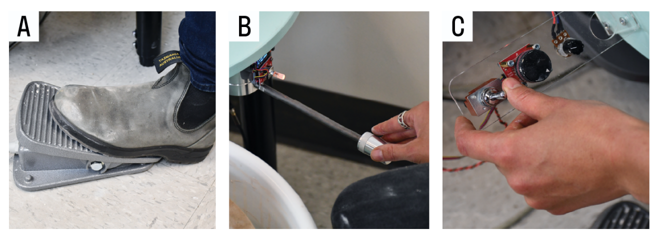

Figure 7: The physical UI of the DPW. A) The foot pedal controls the wheel rotational speed. B) The hand lever controls the angular position of the swing arm. C) The bank of controls attached to the wheel platform includes a switch to toggle between throwing and printing modes, a baby stepping knob to finely adjust the Z-axis carriage position, and an extrusion knob to control the rate of clay deposition.

4.1 Physical UI

The physical user interface (Figure 7) facilitates real-time control over the DPW's four axes for either printing or throwing. It consists of a foot pedal, a hand lever, and a series of knobs and switches. We use a traditional pottery wheel foot pedal to control the wheel's

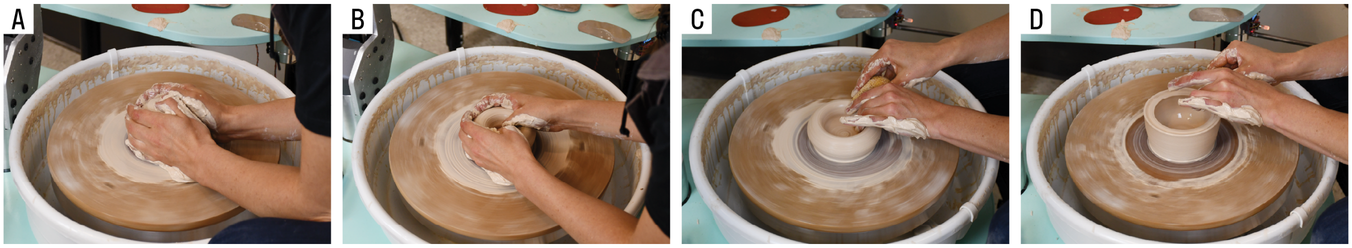

Figure 8: Artist throwing on the DPW. A) The artist centers a ball of clay on the wheelhead. B) The artist creates an opening in the middle of the centered piece of clay. C) The artist pulls the wall up to create a vessel form. D) The artist cleans up the rim.

rotational speed and toggle between mode functionality (Figure 7A). We use a waist-height custom 8-inch hand lever to manually adjust the position of the swing arm with high precision and extremely low latency (Figure 7B). We attached a bank of controls to the left of the wheel that includes: a "baby stepping" knob that finely adjusts the height of the Z-axis carriage, an extrusion knob that controls the clay extrusion rate, and a switch that toggles the mode of the DPW between throwing and printing (Figure 7C). Signals from these inputs are interpreted and converted into appropriate output motion streams by a DPW module we named the "Physical UI Module" (Figure 5A)

4.2 Throwing Interaction

Flipping the physical UI switch to the left toggles the DPW to throwing mode. In this mode, the DPW acts like a commercial 14" pottery wheel. Once the switch is flipped, the Z-axis will lift slightly, and the print arm will move clockwise until the extruder is oriented far out of the way at the 9 o'clock position. All machine controller inputs are disabled except for the wheel, and the physical UI adjusts the pedal's velocity limit to allow the artist to bring the wheel speed up to 250 RPM. In Figure 8, we demonstrate throwing a vessel in throwing mode.

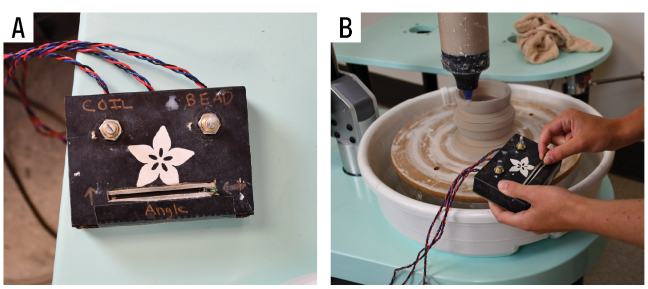

Figure 9: The Pot Assist V1 interaction allows artists to manually print cylindrical forms by controlling the radial and vertical rate of a spiral path. A) The Coil and Bead knobs and Angle slider housed in an Adafruit box during rapid prototyping. B) An artist using the angle slider to create a vase with undulating walls.

4.3 Printing Interactions

Flipping the physical UI switch back to the right causes the arm to swing counter-clockwise until the extruder is positioned over the center of the wheel before enabling all inputs on the machine controller. In printing mode, all axes respond to motion stream inputs on the machine controller, and the Physical UI Module limits the velocity output of the pedal to 50 RPM at the wheel (a value we empirically determined sufficient for printing). We developed several printing interactions:

4.3.1 Printing from G-code. One approach is to print from a pre-made G-code file (Figure 10). Because we use a Duet as input to the Machine Controller, an artist can upload Cartesian G-code generated in a slicer or custom CAM software (Figure 10A) and execute it using the Duet Web Control interface in a manner identical to the Potterbot (Figure 10B). In practice, we uploaded G-code generated using CoilCAM [7]. The DPW control system allows an artist to modify G-code printing in real-time by manipulating the manual controls. The resulting changes will be "mixed" with the G-code signal to determine the printer behavior. Figure 1D shows the same toolpath from Figure 10A, resized with the hand lever to fit the diameter of the hand-thrown vessel in Figure 8.

4.3.2 Assisted Manual Printing. In addition to automated G-code printing, we explored manual printing, where an artist controls the tool printing in real-time. We developed a "Pot Assist" module that simplifies printing radially symmetric forms by mapping physical UI elements to the DPW axes. We developed two iterations, V1 (Figure 9) and V2 (Figure 11) which we describe through sample workflows.

Pot Assist V1 Workflow. To create a cylindrical cup, the artist starts with the extruder at the center of the wheel, approximately 2 mm above the wheelhead. The artist begins the wheel spinning with the pedal. Pot Assist V1 moves the extruder radially at a rate that is coupled to both the wheel's motion and a "coil" control knob (Figure 9A), tracing a spiral path. Simultaneously, the extruder deposits material at a rate proportional to its tangential velocity on the wheel. This process creates a clay base from a spiral coil. The artist uses the linear "angle slider" to build the walls (Figure 9A). The slider begins fully to the left at its "+180 degree" position. The artist moves the slider to the center at its "+90 degree" position. This action causes the arm to lift in the Z direction at a rate proportional to wheel speed and the coil control knob to print the cup walls. The artist can adjust the angle slider to control the printing angle and create undulating walls (Figure 9B). The Pot Assist module synthesizes motion streams for controlling the arm, Z axis, and extruder based on the step rate from the pedal. The motion streams

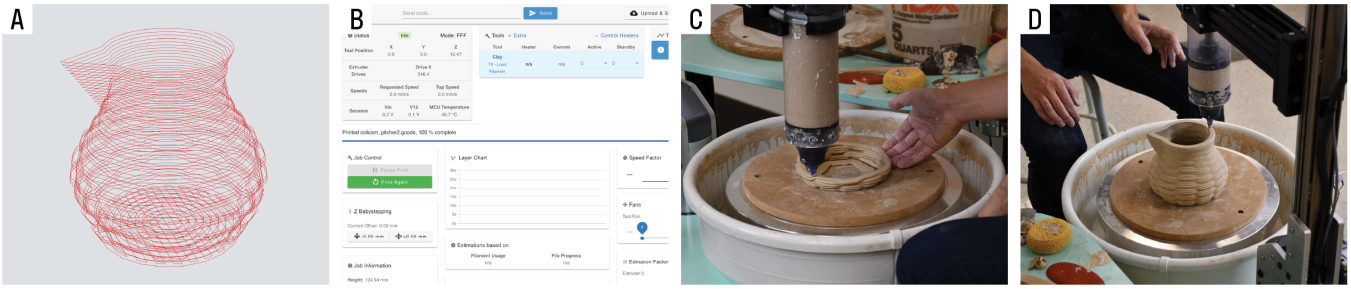

Figure 10: Printing from G-code. A) G-code visualization of a pitcher generated using CoilCAM, a clay-specific CAM-based software. B) The Duet board control interface. C) A pitcher made in CoilCAM being 3D printed on the DPW. D) The completed 3D-printed pitcher.

from the remaining physical UI controls can be mixed with the outputs of the Pot Assist module.

Pot Assist V2 Workflow. During our first artist study sessions, we discovered that the angle slider was confusing because it mapped controls to velocity rather than position change. We created Pot Assist V2 with the hand lever as the primary control. Pot Assist V2 starts in "base mode," in which no Z-axis signal is synthesized (Figure 11A). The base of a pot is created by gently moving the hand lever while spinning the wheel with the pedal to move the arm and print a spiral base. Multiple layers can be created by using the z baby-stepping knob (Figure 11B) to raise the axis after one layer and double the arm back to build another (Figure 11C-E). When the artist completes the base, they stop the wheel by depressing the pedal and then press it again to move into "wall mode," where the Z-axis begins to raise at a rate proportional to the wheel velocity. In wall mode, the artist is free to move the lever (and through it the arm) to create any shape they want, which can include both symmetric and non-symmetric forms (Figure 11F-H).

4.3.3 Record / Playback. Inspired by the audio synthesizer metaphor and historical record playback machining, we created a "Recorder Module" that samples and records four motion streams (one for each axis of the machine) to an onboard SD card. These inputs may be generated using any of the interactions previously mentioned. The artist enters recording mode by pressing the Recorder Module's UI knob (Figure 12A), which causes it to enter recording mode. The onboard display shows the recording time (Figure 12B). During recording, the inputs are both sampled and passed through to the module's outputs, enabling the machine to be controlled while being recorded (Figure 12C). Pressing the knob G-stops recording (Figure 12D). Rotating the module's UI knob to playback mode and pressing it will begin playback (Figure 12E). During playback, the module synthesizes motion streams based on the recording and passes them through the module's outputs, resulting in a verbatim replay of the DPW's motion (Figure 12F). The relative nature of motion streams can be taken advantage of during playback, allowing the same recording to be played repeatedly with different settings mixed in from the manual controls.

5 ARTIST INTERACTION STUDY

We conducted a series of design and feedback sessions with professional ceramic artists. Through this study, we sought to understand how ceramic artists perceived the DPW. In addition, we used the sessions to inform the interaction design of the DPW through participatory design and making. These activities target R2 and R3.

5.1 Methodology

We solicited artists through present and past residents, a local clay studio affiliated with our residency, and artists in a business development workshop conducted in parallel with the residency.

We had nine artists interact with the DPW. Table 1 lists each participant and their experience in manual ceramics and 3D printing. We conducted a mix of individual and group sessions ranging from 40 minutes to three hours, depending on artist availability. The sessions contained the following activities:

(1) **Opening reflections:** Before interaction, artists talked about their reactions to the DPW before interaction.
(2) **Throwing interaction:** Artists threw a vessel while in the DPW throwing mode.
(3) **Demonstration of G-code interaction:** We either printed a pre-prepared G-code toolpath on an empty pottery bat (a removable circular platform placed on the wheel) or printed a portion of a G-code-based structure on top of an artist-thrown vessel.
(4) **Manual interaction with G-code-printed form:** Artists manually adjusted GCode-printed forms on the wheel. We refrained from prescribing specific modifications. Artists worked with printed vessels in whatever manner was interesting or feasible.
(5) **Pot Assist and recording interaction:** We demonstrated Pot Assist V1 or V2. Artists then tried using Pot Assist to fabricate a form. We recorded and played back artists' vessels.
(6) **Closing discussion:** We asked artists to share their reactions following interaction with the wheel.

We conducted six sessions in total, and we adjusted the sequence of interaction activities based on artist experience, interest, and time constraints. For example, we skipped the opening reflection in Session 6 since all participants had discussed the DPW in a previous session. We focused on manual modification of 3D printed forms in Session 6 because Linda reached out following Session 1.

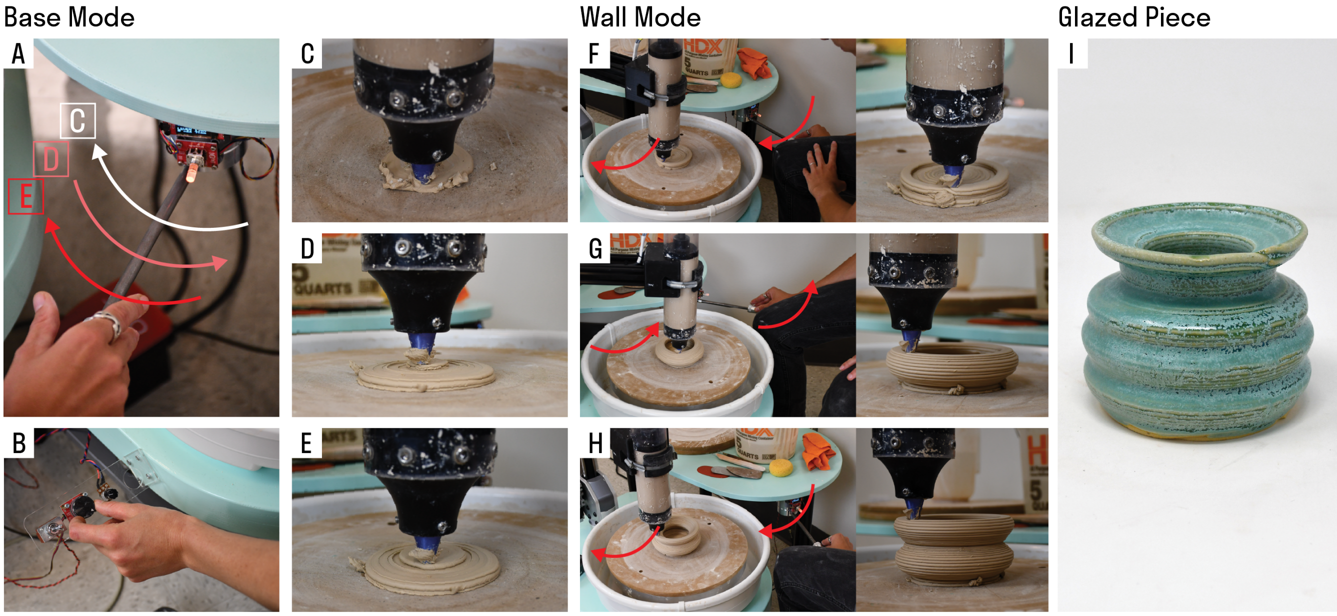

Figure 11: The Pot Assist V2 interaction. A) The artist begins this interaction in base mode when pressing the pedal for the first time. They move the hand lever left, right, and left to create each spiraling base layer. B) Between each base layer, they increase the carriage height by approximately 2 mm using the baby stepping knob. C) The first base layer is generated as a spiral starting from the center of the wheelhead to a radius chosen by the artist. D) The second base layer is created by moving the hand lever inward. E) The third layer is created by moving the hand lever outward again. F) Once the base is completed, the artist stops the wheel with the pedal. The next time they press the pedal, they begin wall mode. They can then move the hand lever outward to open the form and G) inward to close it. H) They repeat these actions to create a desired profile for the piece. I) A final glazed ceramic piece made with Pot Assist V2.

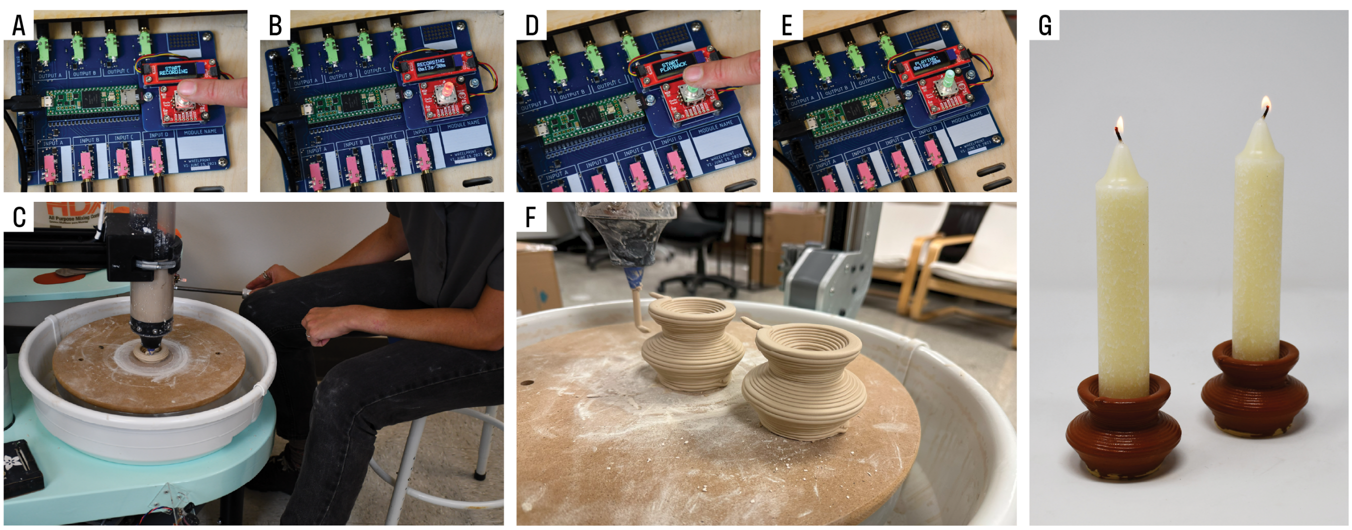

Figure 12: The record and playback interaction. A) The artist begins recording by pressing the knob on the Recorder Module. B) The display indicates the recording time. C) The artist uses the wheel in any printing mode to generate a form. Here, we use Pot Assist V2. D) The artist stops recording by re-pressing the knob. E) Playback is started by rotating the knob and pressing it. F) Two identical vessels created through manual printing and playback. G) The glazed vessels as candlesticks.

Table 1: Artist Backgrounds. The artists in our design study all had prior ceramics experience, with different degrees of expertise across manual clay and clay 3D printing techniques.

Participant	Description	Manual Exp.	3D Printing Exp.	# Years Clay Exp.
Raina Lee	Ceramic artist who creates functional and decorative coiled and thrown vessels for sale.	Wheel throwing, hand building, glaze chemistry	3 months experience clay 3D printing through residency	6
Eun-Ha Paek	Ceramic artist and animator who creates hand-coiled and 3D-printed figurative pieces.	Hand building	Owns a Lutum Clay 3D printer	11
Del Harrow	Ceramic artist who integrates traditional ceramics methods with parametric design and digital fabrication.	Wheel throwing, hand building, mold making	Experienced in computer-aided and parametric design, plastic and clay 3D printing, CNC milling, and other digital fabrication technologies	20
Joey Watson	Ceramic and glass artist who integrates traditional and 3D printed ceramics in his work.	Mold making, hand building, wheel throwing, slip casting	Experienced in computer-aided design, CNC milling, and multiple variations of clay 3D printing	12
Isaih Porter	Professional ceramic craftsperson focusing on functional ware and large-scale thrown pieces.	Wheel throwing	No prior direct experience	10
Pilar Wiley	Ceramic artist and an expert in manual coiling. Creates functional and sculptural clay objects.	Hand building, wheel throwing	3 months experience clay 3D printing through residency	12
Linda Haggerty	Ceramic potter and artist. Professionally trained in wheel throwing but shifted to hand building due to developing arthritis.	Hand building, wheel throwing, manual surface ornamentation	No prior direct experience	40+
James Haggerty	Ceramic potter, artist, and glaze chemist with a focus on wheel-thrown works and custom glaze development.	Hand building, wheel throwing, glaze chemistry	No prior direct experience	40+
Lynda Weinman	Mixed media sculptor and artist working with clay and 3D printing.	No prior direct experience	Owns multiple plastic and clay 3D printers, including large-format clay 3D printers	3

She requested to experiment with throwing 3D-printed forms to compensate for her arthritis. We also focused on Pot Assist V2 in Sessions 5 and 6 after feedback on V1 in Sessions 2 and 3. Table 2 shows each session's participants and interaction sequence.

We audio-recorded discussions and video-recorded and photographed artists' interactions with the DPW. One author took written notes during each session. We bisque-fired all artist pieces and returned the pieces to artists if desired. We transcribed audio recordings, and the authors collectively analyzed the transcripts, written notes, photos, and videos.

Table 2: Session Participants and Interaction Sequence. Sequence numbers correspond to the following session activities: 1) Opening Reflections, 2) Throwing Interaction, 3) Demonstration of G-code interaction, 4) Manual interaction with G-code printed form, 5) Pot Assist and recording, and 6) Closing discussion.

Session	Participants	Sequence
Session 1	Eun-Ha, Raina, Pilar	1,2,3,4,6
Session 2	Eun-Ha, Raina, Pilar, James, Linda	1,2,3,4,5 (V1),6
Session 3	Isaih	1,2,3,4,5 (V1),6
Session 4	Del, Joey, Lynda	1,3,4,6
Session 5	Linda, James, Lynda, Eun-Ha, Raina, Joey	3,4,5 (V2),6
Session 6	Raina	5 (V2),6

5.2 Limitations

Our study varied in structure between sessions, and we report primarily qualitative results. This approach aligned with our objective of understanding the attitudes and experiences of professional ceramicists. Varying session formats enabled us to observe the perspectives of different professionals. Iterating on the DPW interaction functionality during the study allowed us to build interactions that reflected the artists' technical expertise.

5.3 Results

Artists used a combination of interaction modes to produce multiple vessels. Artists felt the throwing mode resembled a standard wheel and saw benefits in integrating throwing and 3D printing. Artists with prior throwing experience identified limitations in the aesthetics and functionality of 3D printed forms.

5.3.1 Working with the DPW in throwing mode. Artists were able to use the throwing mode to throw stable cylindrical vessels, and they perceived the DPW mechanical performance as identical to a standard pottery wheel. Figure 15A and B show Pilar throwing. Isaih threw with the largest amount of clay and stated as he threw that the wheel was "not slowing down at all. . . just what I expect." Artists saw several form differences between the DPW and a standard wheel. Pilar, Raina, and James pointed out the DPW had no space for tools, bats, and slip. Isaih wanted to rotate the wheelhead manually but was prevented by the powered servo, and James noticed the absence of a switch to reverse the wheel rotation direction. The artists who did not use a wheel in their regular process saw benefits to the rotational quality of the DPW and potential in analogies to different rotational pottery tools. For example, Eun-Ha saw an opportunity to structure the DPW at table height to enable her to better manually manipulate the 3D printed coils as they were extruded, in contrast to Cartesian printers.

Artists felt the DPW looked and sounded different from a wheel. Pilar stated that the extruder and z-axis were much louder, and Isaih felt the machine looked "overengineered". The electronic control repeatedly drew attention, and artists felt it was at odds with the dirt and moisture of a ceramic studio. Overall, artists who primarily worked in throwing felt that the rotational feel of the DPW was indistinguishable from a high-end pottery wheel but noted additional functions and qualities for storage, maintenance, and control that were absent from the DPW but standard for pottery wheels.

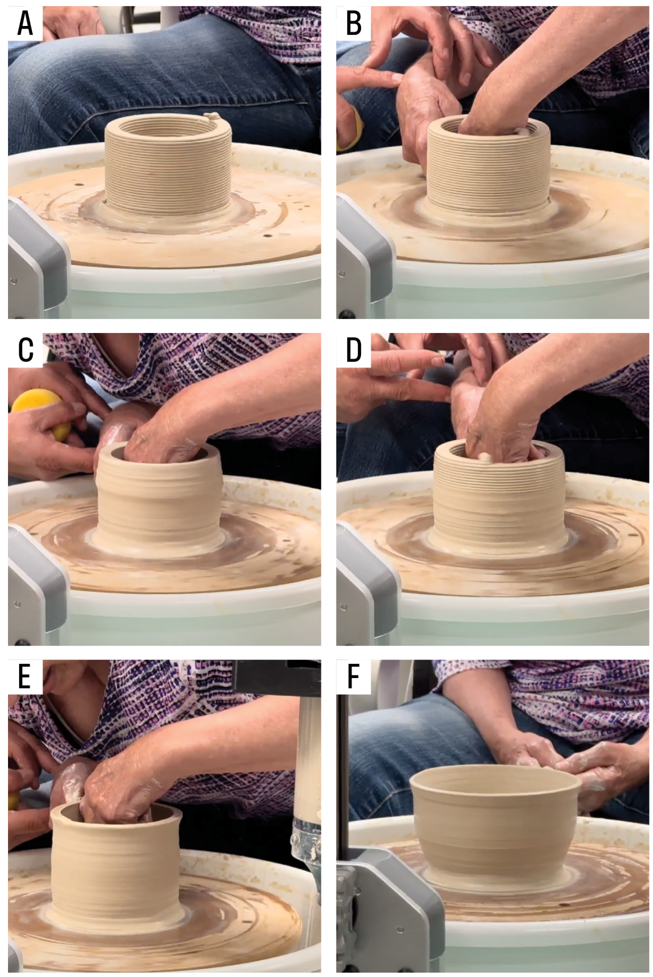

Figure 13: Linda throwing a 3D-printed cylinder into a bowl. A) The printed cylinder prior to throwing. B) Linda makes the first pull to increase the cylinder height and thin the walls. C-D) Linda makes additional pulls to further increase the height. E) Linda begins shaping the cylinder into a bowl. F) The completed bowl.

5.3.2 Manually Manipulating G-code- Printed Forms. Six artists experimented with manually manipulating a 3D printed form on the DPW. James (Figure 17D), Linda (Figure 17E), Raina, and Joey reshaped 3D printed cylinders into vessels with varying diameter. James (Figure 17B) and Del merged together thrown and 3D-printed forms by sealing the seam between them, and in Del's case, by completely re-throwing the 3D printed section. Isaih attempted to rapidly restructure a large cylinder of 3D-printed clay. He ended up tearing the cylinder base off the wheel because 3D printing created less compression on the bottom layer and the wheel surface than he was accustomed to. He subsequently re-centered and threw the torn-off cylinder. Except Isaih, who specifically requested to test the limits of the DPW, artists were able to use throwing to manipulate 3D-printed cylinders. James noted that the 3D-printed layers held up despite his initial concerns about separation.

To ensure extrusion, clay 3D printing requires a higher moisture content than throwing clay. Artists adjusted their throwing technique to compensate for the higher moisture. Del, Raina, and James compressed the base layers of the printed pieces to prevent the piece from collapsing as they pulled the walls upwards. Raina and James felt they could expand the diameter of a 3D printed piece to a lesser degree than hand-centered clay before it would collapse. Raina stated that she would prefer to allow the printed piece to harden slightly before throwing, and without this, thinner or more delicate forms would be difficult to achieve from a 3D-printed starting point.

The artists assessed the quality of the 3D-printed forms by running their fingers over the vessels as the wheel turned. They described material qualities from touching the forms resulting from 3D printing. James felt the extruded coils created a quality similar to coning– where a potter repeatedly pulls up and compresses the clay before opening it:

> *It makes it easy to pull up the piece. This is already doing that for you because if this was a cylinder of fresh wedge clay put on there…I don't think you would've been able to do that kind of pull… You would be fighting against the particles wanting to be in the other direction. So it's almost like it's pre-aligned.*

Raina agreed, stating that this material alignment would "ease the throwing part."

Linda's throwing experience was particularly interesting. Linda was diagnosed with arthritis in her hands at age 19, and this gradually prevented her from throwing on a standard wheel. With the DPW, she successfully threw two vessels starting from five-inch tall 3D-printed cylinders. Linda was excited about the result and remarked, "I never thought I'd ever be able to do something like this ever again." James assisted Linda as she threw and remarked:

> *That really shows a lot of importance behind this tool… You have someone who has a disability with their hands, and they were able to accomplish a thrown piece.*

Figure 13 shows Linda's throwing process with the DPW.

5.3.3 Integrating 3D printing with throwing forms. When artists were willing, we 3D-printed a G-code form on top of the vessel they had manually thrown. Artists used different manual techniques to support this process. Isaih, Raina, Pilar, Del, and James all modified the base thrown form to support the 3D printed coil better. Raina and Pilar threw a thicker form with a wider upper lip to provide sufficient surface area to support the printed coil. Raina reduced the amount of water compared to what she would normally throw with to avoid collapse.

Isaih demonstrated a technique where he threw a vase-like form with a groove in the upper lip (Figure 14A, B). He dried the vessel with a heat gun (Figure 14C). We then 3D-printed a pitcher spout onto the vase using G-code mode (Figure 14D). We used the hand lever to adjust the initial coil to print directly into the groove. After printing, Isaih used throwing mode to seal the seam. He was displeased with the seam and felt he should have sealed it mid-print to achieve a smoother transition. Isaih also noticed the 3D-printed spout was unlikely to pour well. He manually smoothed out the printed coils and reshaped the curve of the spout by hand (Figure 14E, F), stating:

> *I'm pretty particular about my spouts…I like my spouts to come all the way over a little bit, so it's impossible for liquid to get stuck there.*

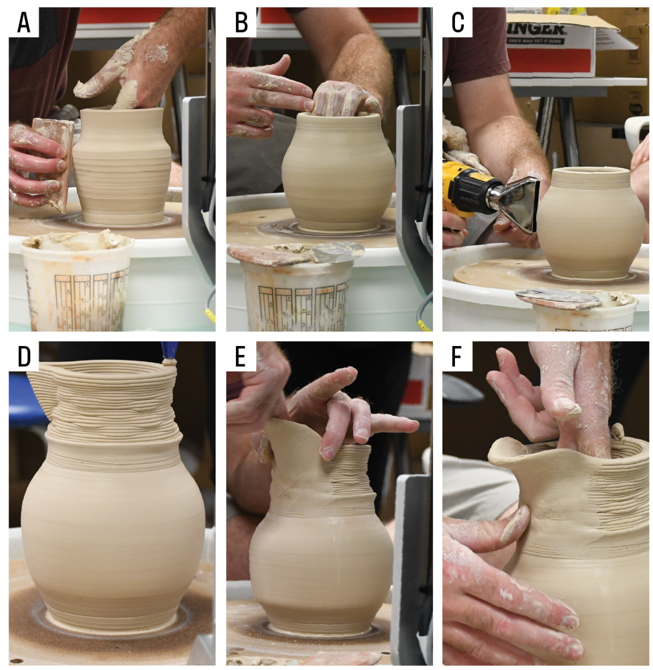

Figure 14: Isaih creating a pitcher with throwing and G-code printing. A) Throwing the base. B) Creating a groove along the top of the base to catch the 3D-printed coil. C) Drying the base slightly to avoid collapse from 3D printing. D) 3D printing the pitcher portion. E, F) Reshaping and smoothing the printed spout manually.

When printing on Pilar's thrown form, James scored the lip with a notched rib to increase the surface area for adhesion (Figure 15C). After a failed print, James removed the printed portion, re-threw the upper lip of the vessel, and repeated the scoring. We then successfully printed a spout on the vessel (Figure 15D). James alternated between using his fingers and a brush to smooth and seal the seam between the thrown and printed pieces, both while the print was executing and after the print was completed in throwing mode

(Figure 15E)). James was unable to smooth out the end of the coil on the upper lip of the printed vessel (Figure 15F)) because he could not reverse the wheel direction.

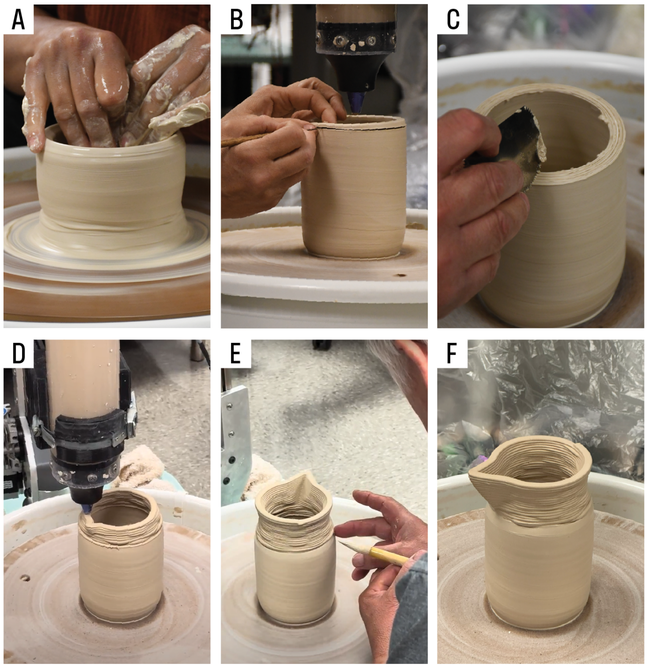

Figure 15: James and Pilar merging a thrown and printed piece. A) Pilar throwing a tall cylinder. B) Pilar trimming the top of the cylinder to a flat surface. C) James scoring the trimmed surface to increase surface area. D) Printing on the thrown vessel. E) James sealing the printed and thrown portions as the wheel rotates. F) The finished vessel.

The artists discussed the benefits of printing on a thrown form on the DPW. Joey felt the DPW made this process significantly easier than moving a thrown form to a Cartesian printer. He stated:

> *[Using a Cartesian 3D printer] wouldn't be impossible. It wouldn't be easy though to register unless your [thrown] pieces were exact every time.*

5.3.4 Interaction with Pot Assist. The artists who used Pot Assist V1 found it difficult to control multiple parameters simultaneously. For example, Isaih stated that "it feels like a lot to control the direction and the height, but also the extrusion rate…It's like one of them has to be taken away." Artists had more positive reactions to V2. In each case, the artist could use it to execute a form. James performed carefully controlled movements to produce a form with a gradually tapering diameter and subtle undulation patterns in the coils. Raina, Joey, and Lynda used V2 more dynamically and produced forms with long unsupported overhanging coils and undulating diameters (Figures 17F and G respectively). Lynda also repeatedly adjusted the z-baby stepping knob while simultaneously moving the lever to produce non-planar toolpaths. Figure 16 documents Raina's use of Pot Assist V2.

Lynda was extremely enthusiastic about V2. She described controlling the machine in this manner as a performative process:

> *I feel like it can have all three modes [G-code printing, manual printing, throwing] and … you could increase the extrusion to make something really gush. You could raise layer height and make things loopy, and if you could do that performatively, I think it would be so much fun.*

James and Raina found V2 more approachable than G-code clay 3D printing. James described himself as "not much of a computer person" and felt the pot assist mode provided "a little bit more of a connection" than G-code printing. He stated, " I consider this of course more, more manual. I get the speed, the timing, the rise." Raina felt a greater degree of immediate control when working with V2. She felt Pot Assist didn't constitute 3D printing and shared more in common with manual clay extruders.

We incorporated Recording with the Pot Assist interactions. Artists were drawn to the potential of recording, but we found it challenging to align the arm with the original starting position of the recording, which resulted in vessels being re-printed at slightly different diameters. Artists experimented with modifying the physical UI parameters during playback to alter the recorded form further. Lynda felt the record and playback feature could be further improved by enabling artists to reproduce past works at larger scales, whereas James and Linda saw potential industrial applications in enabling the automated reproduction of certain aspects of a vessel.

5.3.5 Resulting Artifacts. Across all six sessions, the artists collectively produced 11 vessels. Of these, we bisque-fired 10. Figure 17B-H shows eight bisqued artist pieces. All 10 survived the bisque, and we observed no separation at the seams of 3D printed portions. We found that all 3D-printed geometries had a slight incremental rotational offset in each layer in a clockwise direction (e.g., the spout in figure 17A). This quality occurred because the swing arm traverses an arc, but in our Cartesian-to-polar conversion, we simplified our calculations to assume a linear radius from the wheel center to the arm.

Artists had different reactions to the 3D-printed aesthetics of printed or printed-thrown forms. James and Linda deliberately preserved the 3D-printed coil texture on the top and bottom of two of their pots (Figure 17D), while Joey and Del smoothed them out. Joey appreciated that he could create a vessel that obscured the 3D printed origin, stating that for these pieces, "The only artifact that it was printed will be the foot." Raina, in contrast, was hesitant to manually distort 3D printed portions because of her awareness of the labor and risk involved in Cartesian clay 3D printing:

> *After it prints something really nice like a coil…I just don't want to touch it. [All] this went into loading the tube, and then it printed nice[ly], and all the layers stacked together …After that investment, it's hard to just go and throw it.*

Artists had different perspectives when considering the potential of integrating thrown and 3D printed forms. Eun-Ha and Raina were interested in the surface textures possible through G-code-based printing. Still, both expressed a strong desire to produce forms that had irregular qualities that obscured the computational methods used to produce them. Isaih felt that the G-code-based 3D printed section felt "cold", "a little bit lifeless", and lacked "its human touch."

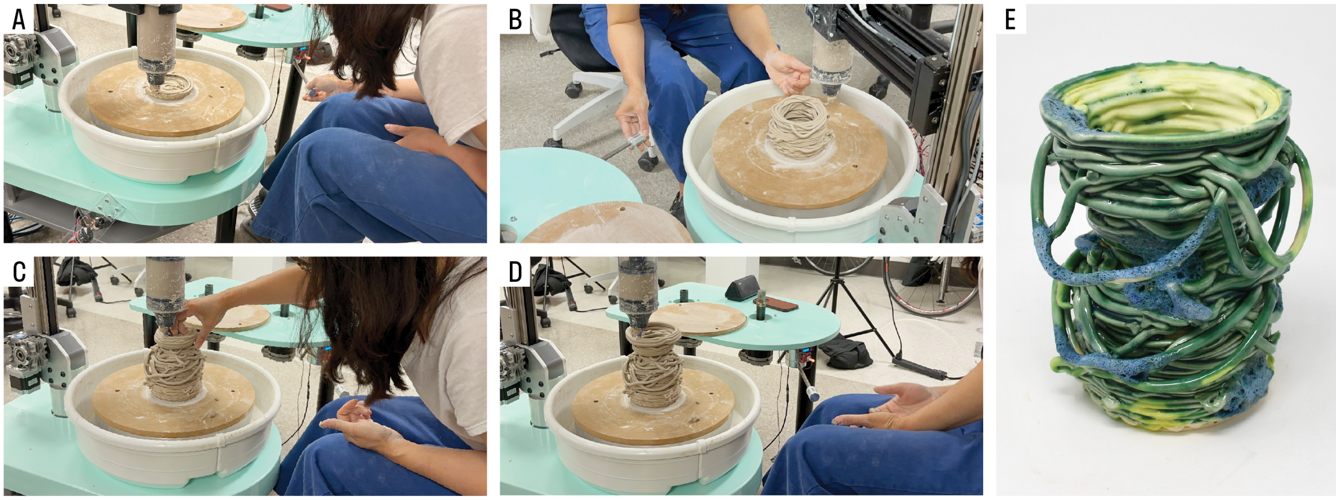

Figure 16: Raina interacting with the Pot Assist V2. A) Raina creates a 1-layer base by moving the hand lever from the middle of the wheelhead to her desired radius and begins creating the wall. B) She moves the extruder outward with the hand lever to create an overhanging texture. C) She pauses the machine to adjust the pot's wall manually. D) She completes her organic-looking vessel. E) Final glazed piece.

He was also skeptical of the functionality of the 3D-printed spout. James and Raina saw potential in glazing works that integrated 3D-printed textures. As James put it:

> *[The pieces] are actually having these textures that sort of bleed out as it goes around the piece. Seeing that in conjunction with the thrown [part], I think, would be absolutely fascinating.*

The forms created with the Pot Assist mode exhibited greater variation and irregularity in their form than those produced through G-code. Lynda appreciated these qualities and was excited about how they might respond to glazing. She felt the process allowed for aesthetics different from Cartesian clay 3D printing.

The Pot Assist polar printing also created new design affordances and constraints. Raina observed that it was easier to produce long, thin forms without collapsing, in contrast to her experience with Cartesian printing. Joey tried to create something that was not a cylindrical vessel, stating, "I don't want to make a pot". He found it difficult to do so.

6 DISCUSSION

We first discuss the outcomes of our CNC mechanical design process and control implementation, namely 1) designing a polar CNC machine and 2) developing a modular and abstracted control system. We then describe the implications of the DPW for traditional ceramics and digital fabrication production by discussing the artifacts, workflows, and perceptions of the artists who used it.

6.1 Implications of Polar Machines and Modular Control for Digital Fabrication

As described in section 3, the DPW is relatively unique among 3D printers. Other 3D printers with rotational or polar mechanisms, like the Scara and the Sculpto, still require the artist to think in Cartesian coordinates to design and control movement. For example, to move the Scara to a given point, the artist inputs an x,y position, which rotates its three primary joints to move the end effector to that position. In our experience, this rotation is challenging to predict. By contrast, the DPW uses polar coordinates as input to output to polar mechanism movement, thereby supporting *design action* and *control* in polar space. We argue this "polar way of thinking" can reduce the gulf of understanding between the machine controls and the machine action, which is critical for interactive and real-time fabrication workflows. Further, polar relationships map to existing pottery techniques. Potters adjust the diameter of a vessel by drawing their hands or a tool towards or away from the center of the wheel. This process is similar to how the DPW swing arm sets the "radius" of a printed coil.

The DPW design has implications for new CAD and CAM design methods. We can re-envision CAD and CAM workflows that align with the polar coordinates of the DPW. For the lathe, another rotational CNC, part design is generally specified in terms of diameter and length. One could apply a similar set of design parameters for the DPW, wherein vessels for automated fabrication are not defined in terms of meshes or solid geometry and then sliced but rather as a varying diameter profile.

The DPW control system similarly offers a new way to think about what constitutes CNC control. Our modular design reflects a physical "dataflow system" similar to digital dataflow languages [12, 43], which were also inspired by modular synthesizers.

We initially envisioned that the modular approach might also enable artists to reconfigure the DPW to their needs by adding, removing, or altering the sequence of physical modules like a modular synthesizer performer. During our prototyping process and artist study, we quickly realized that this was infeasible. For one, we found that keeping track and correctly attaching inputs was cognitively demanding for the authors, let alone for someone who

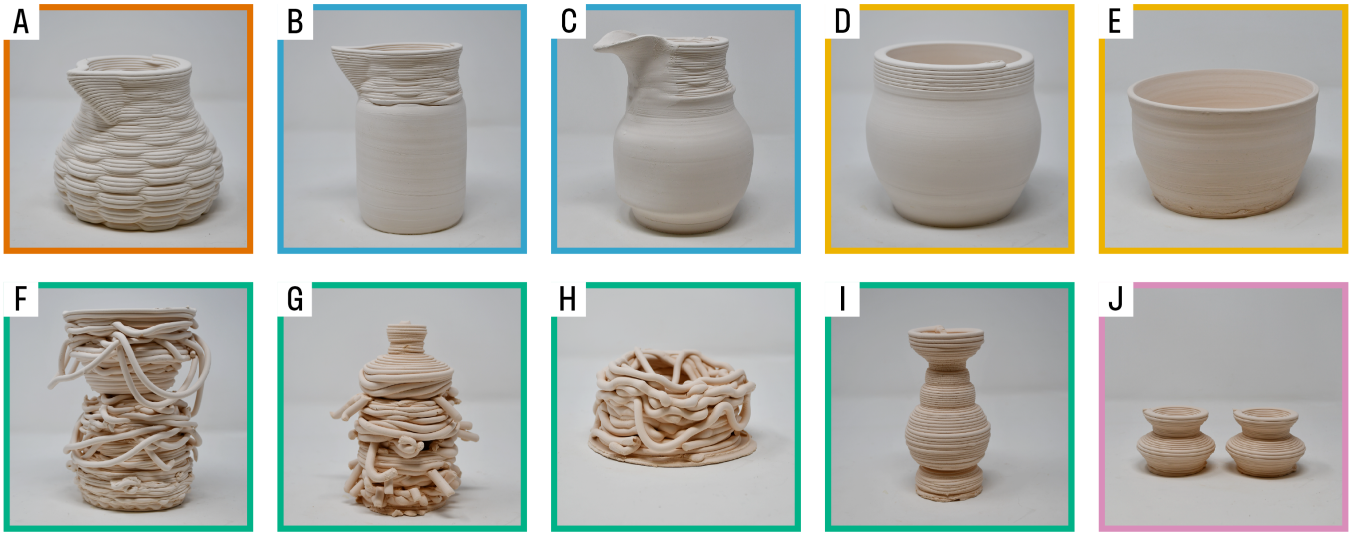

Figure 17: G-code printing: A) 3D-printed jug designed by the authors. Throwing and G-code-printing on top: B) Base thrown by Pilar with 3D-printed spout merged by James. C) Base thrown by Isaih with 3D printed spout manually modified by Isaih. Throwing the G-code-printed artifacts: D) 3D-printed cylinder thrown by James. E) 3D-printed cylinder thrown by Linda. Pot Assist: F) Pot made by Raina with the Pot Assist mode. G) Pot made by Lynda with the Pot Assist mode. H) Pot made by Joey with the Pot Assist mode. I) Pot made by Samuelle with the Pot Assist mode. Pot Assist and Playback: J) Pot made by Samuelle with the Pot Assist mode, recorded and replayed, creating a second identical pot.

had not engineered the system. Additional study on modular synth design and organization strategies would likely yield insights on how to improve the assembly of our modules. While we are uncertain about the degree to which artists would benefit from access to a modular control system, it was extremely beneficial for us as developers. In addition to the fact that the modularity allowed us to design and iterate on multiple interactions, our control system reframed how we thought about CNC conventions as our development progressed. The primary example in this regard is the use of G-code. Initially, we required the Duet and pre-programmed G-code to support fully automated printing. Later, we implemented the recorder module, which allowed us to record and store any G-code file we originally ran through the Duet. The combination of manual manipulation and recording effectively rendered the G-code mode "vestigial" for the purposes of our research. Through study with artists, we realized that because we could modify G-code with the physical UI and throwing, we only needed a limited number of basic G-code files that could be parameterized at will by the artist. This observation suggests that we could conceptually eliminate G-code functionality from the machine by removing the requirement to program a toolpath on a desktop computer. We could further literally eliminate G-code by unplugging the Duet from the machine controller without impacting any other functionality. We argue this process has implications for the stability of CNC conventions. The DPW demonstrates that we can remove a central convention for digital fabrication control without losing meaningful forms of digital expression.

6.2 Products: Distinctions Between DPW Artifacts and Those Produced With a Cartesian 3D printer

One of our primary design goals was for the DPW to maintain parity with the capabilities of existing clay 3D printers despite using a wheel mechanism and a polar coordinate system. Our demonstrative artifacts from the G-code printing mode show that the DPW is capable of printing regular cylindrical G-code toolpaths with the same degree of fidelity as Cartesian printers. Further, the DPW can print irregular G-code forms, with the caveat of the offset in layer rotation due to the swing arm arc (Figure 17A). We believe it would be possible to compensate for this in our Cartesian-to-polar conversion calculation.

DPW also allows for printing artifact qualities that are challenging to achieve with Cartesian 3D printing. First, DPW affords printing tall slender vessels. On a 3D printer with serial Cartesian kinematics, the shift in the x-y direction of the bed exerts forces on the printed piece. As a result, tall and narrow pieces frequently collapse during printing. In contrast, when printing in G-code or Pot Assist mode, the DPW maintains a constant speed and direction while printing. We observed that this allowed for the fabrication of narrow, overhanging cylindrical structures without collapse. This quality was particularly evident to Raina. Second, the DPW Pot Assist mode supports the creation of long and irregular looping overhangs. These qualities are evident in the pieces produced by Raina, Lynda, and Joey (Figures 17F, G, and H, respectively). Such structures are much more challenging to produce with a Cartesian 3D printer because they require toolpaths that cannot be produced with a standard slicer. To produce irregular and organic loops like those in our results, artists primarily use symbolic programming and numerically specify the irregular shape of the toolpath [7]. The same applies to non-planar toolpaths, like those Lynda and Joey achieved with the z-baby stepping. Pot Assist instead enables artists to describe these qualities through their gestures. A recent alternative to numerical digital toolpath specification is SketchPath [24]– a drawing-based CAM design tool that supports the creation of irregular hand-drawn toolpaths. We see opportunities to integrate the digital direct manipulation of SketchPath with the physical direct manipulation of the DPW.

The artifacts produced through integrating throwing mode and printing further differentiate DPW's output from Cartesian printers because they combine the very distinct aesthetics of clay 3D printing (e.g., visible coils and intricate surface texture) with the aesthetics of wheel-thrown forms (e.g., smooth surfaces, finger threading, and variable wall thickness). Integrating thrown characteristics into a 3D printed form is also important from a functional perspective. As Isaih described, smooth surfaces ensure liquids flow smoothly out of the vessel. The alignment of clay particles from throwing produces vessels that are simultaneously thin and compacted and, thus, more likely to survive firing and use. Throwing also allows for variable wall thickness–something that has only recently become possible with clay 3D printing [23]. Wall thickness is a critical aesthetic and functional quality in ceramic vessels. The DPW opens future opportunities to combine clay-specific toolpathing approaches like those of Friedman-Gerlicz *et al.* with manual manipulation to create robust functional ceramic vessels.

The DPW's outputs are primarily limited in comparison to Cartesian 3D printers in that it is difficult to produce an artifact that, in Joey's words, is "not a pot". This limitation is most evident in the pot assist mode; however, it is also present in the G-code printing mode. If artists choose to throw on an irregular 3D printed form, they must strategically plan the order of operations to avoid collapsing or distorting the non-cylindrical pieces. As a result, in its current form, the DPW is perhaps less appropriate for ceramic artists who produce sculptural forms rather than vessels. Given that we sought to develop the DPW as a wheel– a device that has long served as a means for vessel-making– this constraint is directly aligned with our design goal.

We recognize that the DPW mechanism presents a greater cost and manufacturing complexity than Cartesian printers. We argue that these tradeoffs are meaningful because, through them, we enable new 3D clay artifacts that are prohibitively difficult to produce through standard printing methods.

6.3 Workflows: How the DPW Shapes the Process of Working with Clay for Artists.

We prioritized the functionality of a pottery wheel in the DPW mechanical architecture. We then used our reconfigurable control system to explore workflows that leveraged the co-location of a 3D printing mechanism and a wheel. We discuss how these resulting workflows align with manual throwing and their uniqueness in contrast to those possible with existing tools.

While we were successful in many respects in replicating the functionality of a standard wheel, artists noted the DPW lacked several key throwing capabilities. Many of these functions are compatible with our current design. The servo that drives the wheel is bidirectional, and adding a physical switch to change rotation during throwing mode would be straightforward. Further, we could support alternate rotation directions during printing modes by modifying the machine controller software. These are additions we are currently pursuing. Similarly, adding storage space or changing the wheel's height would be possible by reconfiguring the deck and leg geometry. However, we would need to assess how this would impact machine stability. Allowing the wheelhead to be manually rotated by hand is possible with a software modification to assert the wheelhead servo's disable input. This action could be triggered by a physical control switch. Further experimentation is needed to determine whether the wheel spins with sufficient freedom when the servo is disabled.

The combination of throwing mode and 3D printing introduced new requirements for throwing: artists had to work with clay with greater moisture content when throwing 3D printed pieces. When throwing forms to be 3D printed on, artists had to use less moisture and control the thickness of the piece to a greater degree to avoid collapse. They also had to compress and seal printed coils to ensure robustness and manipulate thrown vessel rims to enable printing on top. These constraints were different than those present in non-digital throwing workflows; however, they were also well within the skill set of experienced potters. In this way, DPW preserves the role of manual throwing skill and afforded *skilled workflows* for digital-manual ceramics production.

It is also critical to discuss how the workflows in our study are unique properties of the DPW or whether they could also be performed with the combination of a standard pottery wheel and a Cartesian clay 3D printer. First, we consider the workflow of *throwing to 3D printing* (e.g., 3D printing on a thrown form). As the artists in our study indicated, while this is possible with a Cartesian clay 3D printer, it is complex. An artist would have to measure the thrown vessel and modify a toolpath to have the correct diameter. Then, they would have to align the thrown section precisely on the printer bed to ensure accurate placement of the printed portion. The process of printing on existing objects is equally complex in thermoplastic printing. HCI researchers have employed computational analysis [10], computer vision object tracking [89], and optimization algorithms [47] with pre-defined physical objects [84] to facilitate such workflows. The DPW circumvents the need for precise manual or computational alignment strategies. Instead, we integrate manual adjustment and automated 3D printing; by moving the extruder with the swing arm lever, the artist can dynamically adjust the diameter of a pre-defined G-code toolpath to match the diameter of the thrown pot on the wheel. These advantages are the combined result of integrating a 3D printer and a wheel in the same machine and the adoption of *both* polar coordinates and a polar positioning mechanism for 3D printing. Expressing the toolpath in polar coordinates exposes the domain-relevant parameter of radius for direct real-time modification. The DPW polar positioning mechanism, in turn, allows the user to intuitively and visually reason about this affordance of the system– manually adjusting the radial position of the swing arm while printing results in predictable changes to the print radius. As a result, the DPW supports a throwing to 3D printing workflow that prioritizes manual control and is significantly less demanding than existing tools.

Second, we consider the workflow of *3D printing to throwing* (e.g., using throwing to alter a form that has been 3D printed). This process is currently feasible with a Cartesian printer and standard wheel. One possible workflow is to print a cylindrical vessel, allow it to dry slightly, and then use manual centering or a trimming chuck [33] to center it on a standard wheel. We observed a past resident do exactly that. An alternative workflow would be to ensure a pottery bat is precisely centered on the printing bed and then to develop a toolpath that prints the center of the vessel at the center of the bed. This process will ensure that when the bat is fitted to the wheel, the vessel will already be centered. The benefit that the DPW provides over established tools for the printing-to-throwing workflow differs from that of throwing to printing. In this case, the DPW makes an existing workflow more immediate and reduces the number of interruptions in the fabrication process. Immediacy is often critical in creative workflows. When working across physical and digital mediums, artists can experience unproductive breakdowns when they must perform additional labor to transfer their work to tools with different requirements [40]. We see benefits in digital fabrication technologies that integrate different working modes while reducing friction across these modes. We also see opportunities from the fact some of DPW's workflows are feasible with existing tools. Artists in our study, particularly Linda, perceived clear benefits to the ability to throw with a 3D-printed base form. The fact that it would be feasible to streamline this workflow with commercially available tools suggests another avenue for engaging potters in clay 3D printing.

Third, we consider the *Pot Assist workflow* in comparison to Cartesian 3D printing. Cartesian 3D printing requires extensive design before material fabrication. As Raina and Eun-Ha described, the artist's primary manual interventions during Cartesian clay 3D printing fabrication involve responding to printing errors. With Pot Assist, the primary design activity occurs simultaneously with the fabrication process. Artists can make aesthetic and structural decisions about the vessel structure by observing the behavior of the material and the machine in real time. In this way, Pot Assist is similar to throwing, except that in throwing, artists can also leverage physical material feedback in their decision-making process.

The throwing to printing, printing to throwing, and pot assist workflows show how DPW's integration of a wheel and extruder on a polar mechanism supports workflows that are different from those that are readily available with a Cartesian clay 3D printer while preserving (and in some cases requiring) manual throwing skill. Further, combining 3D printing and manual fabrication with the DPW suggests that digital fabrication automation can function in ways other than as a fully automated technology for "unskilled" creators [94]. The workflows we observed with the DPW add further evidence for Devendorf and Rosner's argument of the limitations of the "hybrid" model of human-machine craft. Hybrid craft presents a categorization where humans excel at creativity and machines excel at automation and precision [16]. Our work reinforces how more nuanced models are required to understand human-digital fabrication interaction. In the case of the DPW, we observed how human skill can preserve machine expression, how human precision can accommodate machine constraints, and how machine automation can facilitate human playfulness.

6.4 Perceptions: How the DPW Form Impacted Artists' Perceptions of its Applications.

We theorized that designing a clay 3D printer that looked and felt like a wheel might positively impact practitioners' perceptions of what "could" be done with such a tool and their motivation and confidence in working with digital technology. Our theory relates to Li *et al.'s* concept of the *normative ground* of a creativity support tool– how the tool features and constraints collectively structure not only what artists can practically accomplish but also hold *power over* how artists think and react [41]. While Li's analysis focused primarily on representation in software tools, we can expand the concept of normative ground to the physical representation of a fabrication tool.

The descriptive language and analogies artists used to refer to the DPW provide some insights into their perceptions of its applications. Artists' noted that the tool resembled a pottery wheel or a pottery wheel with a 3D printer attached. Artists also used analogies to other traditional pottery tools, including a banding wheel and a manual clay extruder.

Artists with prior digital fabrication experience perceived the capabilities of the wheel relative to their experience with clay 3D printing. Eun-Ha saw the wheel as a polar printer that could better support manual manipulation during printing. Lynda and Del described it as a *performative or collaborative instrument*, in the sense that the integration of the wheel, manual control, and automated printing enabled a compelling production process in and of itself, in addition to the artifacts produced. We should note that the group study structure may have contributed to performance associations since an audience was always present.

Artists also brought unexpected associations to DPW, including a device to aid people with physical disabilities, a platform to help people learn how to throw, and a device to scaffold the process of learning clay 3D printing. Lynda felt while many traditional potters would be unlikely to use Cartesian 3D printers, they might be willing to use the DPW.

These statements indicate that the form of a digital fabrication machine can shape people's conceptions of how it might be used. Foremost, artists viewed the DPW as a wheel, which aligned with our original design goal. While further study is required to determine if and how DPW could be meaningful in performative, learning, or accessibility settings, these potential applications show how the DPW elicited *enabling* associations among the artists in our study.

Although artists had positive perceptions of the wheel, they were more skeptical of the control system. They felt the electronics might be incompatible with a clay studio, were complex in appearance, and likely costly. For example, Raina referred to the control system as an "exposed brain," and Isaih speculated that the cost would be prohibitive, stating " I can't imagine what you sell this for, but potters are not the wealthiest." When discussing the degree to which the control could be modified to support greater degrees of automation, Linda described her concerns:

> *If [the DPW] goes buggy on me and it starts to do something weird and I'm not sure how to fix it. . . I would want to at least be able to bypass that and be able to do it myself. Practically speaking who is going to fix it? Less automation would be better.*

We developed the control modules with a different objective from the wheel– supporting rapid prototyping rather than maintaining visual familiarity with established pottery tools. Despite this, there is something to be learned from artists' observations. As Linda and Isaih's quotes indicate, professional artists evaluate tools on more than the outcomes they can produce. They equally consider cost, maintenance, and transparency factors because they rely on these tools for their livelihood. HCI researchers have envisioned future forms of fabrication in which we can augment existing tools, machines, or environments with increasingly complex "smart" digital capabilities [4]; however, maintenance is already a substantial undertaking for contemporary digital fabrication technologies [74]. Our research shows how individual professional artists will rightly identify new costs that result from augmenting their existing tools. As researchers, we, therefore, must evaluate the potential benefits of digital tool augmentation in relation to the degree to which they are likely to enact *power over* artists and workers through new forms of labor and maintenance and their associated costs.

7 CONCLUSION

This work documents the Digital Pottery Wheel, a manual-digital clay fabrication tool inspired by manual pottery technologies. We drove our research through the physical metaphor of a CNC as a pottery wheel. In doing so, we sought to avoid imposing industrial CNC machine constraints on craft practice, and instead, extended Ingold's framing to *follow the materials* of manual pottery technologies [34]. By bringing the technical expertise of ceramic artists to bear in our interaction design process, we show how a CNC design process structured around a physical metaphor can reshape perceptions and practices in 3D printing.

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REFERENCES

[1] Lea Albaugh, Scott E Hudson, and Lining Yao. 2023. An Augmented Knitting Machine for Operational Assistance and Guided Improvisation. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3544548.3581549

[2] All3DP. 2023. The Types of FDM 3D Printers: Cartesian, CoreXY & More. https://all3dp.com/2/cartesian-3d-printer-delta-scara-belt-corexy-polar/

[3] C. Anderson. 2012. *Makers: The New Industrial Revolution.* Crown, New York.

[4] Michelle Annett, Tovi Grossman, Daniel Wigdor, and George Fitzmaurice. 2019. Exploring and Understanding the Role of Workshop Environments in Personal Fabrication Processes. *ACM Transactions on Computer-Human Interaction* 26, 2 (March 2019), 10:1–10:43. https://doi.org/10.1145/3301420

[5] Patrick Baudisch and Stefanie Mueller. 2017. Personal Fabrication. *Foundations and Trends in Human–Computer Interaction* 10, 3–4 (2017), 165–293. https://doi.org/10.1561/1100000055

[6] Patrick Baudisch, Stefanie Mueller, Thijs Roumen, Pedro Lopes, Robert Kovacs, Jotaro Shigeyama, Shohei Katakura, Muhammad Abdullah, Conrad Lempert, Martin Taraz, and Lukas Rambold. 2023. Pushing Fabrication Research past the Makers. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems (CHI EA '23)*. Association for Computing Machinery, New York, NY, USA, 1–5. https://doi.org/10.1145/3544549.3583922

[7] Samuelle Bourgault, Pilar Wiley, Avi Farber, and Jennifer Jacobs. 2023. CoilCAM: Enabling Parametric Design for Clay 3D Printing Through an Action-Oriented Toolpath Programming System. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–16. https://doi.org/10.1145/3544548.3580745

[8] Sarah Rosalena Brady. 2020. transposing a form. https://www.sarahrosalena.com/transposing-a-form Publication Title: Sarah Rosalena.

[9] Leah Buechley and Ruby Ta. 2023. 3D Printable Play-Dough: New Biodegradable Materials and Creative Possibilities for Digital Fabrication. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3544548.3580813

[10] Xiang 'Anthony' Chen, Stelian Coros, Jennifer Mankoff, and Scott E. Hudson. 2015. Encore: 3D Printed Augmentation of Everyday Objects with Printed-Over, Affixed and Interlocked Attachments. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. Association for Computing Machinery, New York, NY, USA, 73–82. https://doi.org/10.1145/2807442.2807498

[11] Creality. 2023. Ender-3 Pro 3D Printer. https://www.creality.com/products/ender-3-pro-3d-printer

[12] Scott Davidson. 2007. Grasshopper. http://www.grasshopper3d.com

[13] Audrey Desjardins and Timea Tihanyi. 2019. ListeningCups: A Case of Data Tactility and Data Stories. In *Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19)*. Association for Computing Machinery, New York, NY, USA, 147–160. https://doi.org/10.1145/3322276.3323694

[14] Audrey Desjardins, Timea Tihanyi, Freesoul El Shabazz-Thompson, Brock Craft, and Julia Saimo. 2023. THE INNER EAR: CAPTURING AND PHYSICALIZING HOME VIBRATIONS. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference (DIS '23)*. Association for Computing Machinery, New York, NY, USA, 594–607. https://doi.org/10.1145/3563657.3596070

[15] Laura Devendorf, Katya Arquilla, Sandra Wirtanen, Allison Anderson, and Steven Frost. 2020. Craftspeople as Technical Collaborators: Lessons Learned through an Experimental Weaving Residency. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376820

[16] Laura Devendorf and Daniela K. Rosner. 2017. Beyond Hybrids: Metaphors and Margins in Design. In *Proceedings of the 2017 Conference on Designing Interactive Systems - DIS '17*. ACM Press, Edinburgh, United Kingdom, 995–1000. https://doi.org/10.1145/3064663.3064705

[17] Laura Devendorf and Kimiko Ryokai. 2015. Being the Machine: Reconfiguring Agency and Control in Hybrid Fabrication. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*. ACM Press, Seoul, Republic of Korea, 2477–2486. https://doi.org/10.1145/2702123.2702547

[18] Nir Dick, Naama Glauber, Adi Yehezkeli, Moran Mizrahi, Shani Reches, Maiayn Ben-Yona, Anna Carmi, and Amit Zoran. 2018. Design with Minimal Intervention: Drawing with Light and Cracks. In *Proceedings of the 2018 Designing Interactive Systems Conference (DIS '18)*. Association for Computing Machinery, New York, NY, USA, 1107–1120. https://doi.org/10.1145/3196709.3196814

[19] Duet3D. 2023. Duet 3 Mainboard 6XD. https://docs.duet3d.com/Duet3D_hardware/Duet_3_family/Duet_3_Mainboard_6XD_Hardware_Overview

[20] Duet3D. 2023. Duet3D. https://www.duet3d.com/

[21] Eazao. 2023. Matrix Clay 3D printer. https://www.eazao.com/matrix/

[22] Jacob Foran and Phirak Suon. 2022. ForanSuon Porcelain Collection. https://www.foransuon.com/porcelain-collection Publication Title: ForanSuon Studio.

[23] Camila Friedman-Gerlicz, Deanna Gelosi, Fiona Bell, and Leah Buechley. 2024. WeaveSlicer: Expanding the Range of Printable Geometries in Clay. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, Hawaii) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3613904.3642622

[24] Devon Frost, Eun-Ha Paek, Raina Lee, and Jennifer Jacobs. 2024. SketchPath: Using Digital Drawing to Integrate the Gestural Qualities of Craft in CAM-Based Clay 3D Printing. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, Hawaii) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3613904.3642684

[25] Michelle Gantt and Bonnie A. Nardi. 1992. Gardeners and gurus: patterns of cooperation among CAD users. In *Proceedings of the SIGCHI Conference on Human*

Factors in Computing Systems (CHI '92). Association for Computing Machinery, New York, NY, USA, 107–117. https://doi.org/10.1145/142750.142767
[26] N.A. Gershenfeld. 2005. *Fab: The Coming Revolution on Your Desktop–from Personal Computers to Personal Fabrication.* Basic Books, New York.
[27] Jamison Go, Scott N. Schiffres, Adam G. Stevens, and A. John Hart. 2017. Rate limits of additive manufacturing by fused filament fabrication and guidelines for high-throughput system design. *Additive Manufacturing* 16 (2017), 1–11. https://doi.org/10.1016/j.addma.2017.03.007
[28] Sarah Goehrke. 2014. Dutch Company VormVrij 3D Uses Clay to 3D Print Huge Ceramic Pieces. https://3dprint.com/21982/vormvrij-3d-print-clay/
[29] Ammar Hattab and Gabriel Taubin. 2019. Rough carving of 3D models with spatial augmented reality. In *Proceedings of the 3rd Annual ACM Symposium on Computational Fabrication (SCF '19)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3328939.3328998
[30] Mare Hirsch, Gabrielle Benabdallah, Jennifer Jacobs, and Nadya Peek. 2023. Nothing Like Compilation: How Professional Digital Fabrication Workflows Go Beyond Extruding, Milling, and Machines. *ACM Trans. Comput.-Hum. Interact.* 31, 1, Article 13 (nov 2023), 45 pages. https://doi.org/10.1145/3609328
[31] Melody Horn, Amy Traylor, and Leah Buechley. 2022. Slabforge: Design Software for Slab-Based Ceramics. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3491102.3517663
[32] Matthew B. Hoy. 2013. 3D Printing: Making Things at the Library. *Medical Reference Services Quarterly* 32, 1 (Jan. 2013), 93–99. https://doi.org/10.1080/02763869.2013.749139 Publisher: Routledge _eprint: https://doi.org/10.1080/02763869.2013.749139.
[33] Giffin Tec inc. 2023. Giffin Grip Model 10. https://www.giffingrip.com/shop-test/giffin-grip-model-10
[34] T. Ingold. 2010. The textility of making. *Cambridge Journal of Economics* 34, 1 (Jan. 2010), 91–102. https://doi.org/10.1093/cje/bep042
[35] Sonny Jeon, Simen Svale Skogsrud, Elijah Insua, Bertus Kruger, Jens Geisler, Martin Poelstra, and Rob Brown. 2023. grbl/grbl. https://github.com/grbl/grbl original-date: 2009-01-24T23:47:13Z.
[36] Jonathan Keep. 2020. A Guide to Clay 3D Printing.
[37] Jonathan Keep. 2022. Jonathan Keep. Home Page. http://www.keep-art.co.uk/
[38] Kniterate. 2023. Kniterate: the Digital Knitting Machine. https://www.kniterate.com/product/kniterate-the-digital-knitting-machine/
[39] Joong Han Lee. 2011. joong han lee: haptic intelligentsia. https://www.designboom.com/design/joong-han-lee-haptic-intelligentsia-2/
[40] Jingyi Li, Sonia Hashim, and Jennifer Jacobs. 2021. What We Can Learn From Visual Artists About Software Development. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3411764.3445682
[41] Jingyi Li, Eric Rawn, Jacob Ritchie, Jasper Tran O'Leary, and Sean Follmer. 2023. Beyond the Artifact: Power as a Lens for Creativity Support Tools. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (<conf-loc>, <city>San Francisco</city>, <state>CA</state>, <country>USA</country>, </conf-loc>) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 47, 15 pages. https://doi.org/10.1145/3586183.3606831
[42] Pedro Lopes, Doăa Yüksel, François Guimbretière, and Patrick Baudisch. 2016. Muscle-plotter: An Interactive System based on Electrical Muscle Stimulation that Produces Spatial Output. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. Association for Computing Machinery, New York, NY, USA, 207–217. https://doi.org/10.1145/2984511.2984530
[43] Cycling74 2017. *Max.* Cycling74. https://cycling74.com/products/max/.
[44] Daniela Mitterberger, Selen Ercan Jenny, Lauren Vasey, Ena Lloret-Fritschi, Petrus Aejmelaeus-Lindström, Fabio Gramazio, and Matthias Kohler. 2022. Interactive Robotic Plastering: Augmented Interactive Design and Fabrication for On-site Robotic Plastering. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22)*. Association for Computing Machinery, New York, NY, USA, 1–18. https://doi.org/10.1145/3491102.3501842
[45] Ilan E. Moyer. 2012. CoreXY: Cartesian Motion Platform. https://corexy.com/
[46] Stefanie Mueller, Pedro Lopes, and Patrick Baudisch. 2012. Interactive construction: interactive fabrication of functional mechanical devices. In *Proceedings of the 25th annual ACM symposium on User interface software and technology (UIST '12)*. Association for Computing Machinery, New York, NY, USA, 599–606. https://doi.org/10.1145/2380116.2380191
[47] Stefanie Mueller, Tobias Mohr, Kerstin Guenther, Johannes Frohnhofen, and Patrick Baudisch. 2014. faBrickation: fast 3D printing of functional objects by integrating construction kit building blocks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. Association for Computing Machinery, New York, NY, USA, 3827–3834. https://doi.org/10.1145/2556288.2557005
[48] Michael Muller and Allison Druin. 2002. Participatory Design: The Third Space in HCI. In *Handbook of HCI*. CRC Press, Boca Raton.
[49] mycusini. 2023. mycusini 2.0 3D Chocolate Printer. https://mycusini.com/en/products/mycusini-2-0-3d-schokodrucker
[50] J.R. Napier and R.H. Tuttle. 1993. *Hands.* Princeton University Press, Princeton. https://books.google.com/books?id=mNQM4jvG7hgC
[51] David F. Noble. 2013. *Forces of Production.* Knopf Doubleday Publishing Group, New York.
[52] Nadya Peek, James Coleman, Ilan Moyer, and Neil Gershenfeld. 2017. Cardboard Machine Kit: Modules for the Rapid Prototyping of Rapid Prototyping Machines. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 3657–3668. https://doi.org/10.1145/3025453.3025491
[53] Nadya Peek and Ilan Moyer. 2017. Popfab: A Case for Portable Digital Fabrication. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction (TEI '17)*. Association for Computing Machinery, New York, NY, USA, 325–329. https://doi.org/10.1145/3024969.3025009
[54] Huaishu Peng, Jimmy Briggs, Cheng-Yao Wang, Kevin Guo, Joseph Kider, Stefanie Mueller, Patrick Baudisch, and François Guimbretière. 2018. RoMA: Interactive Fabrication with Augmented Reality and a Robotic 3D Printer. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3174153
[55] Huaishu Peng, Amit Zoran, and François V. Guimbretière. 2015. D-Coil: A Hands-on Approach to Digital 3D Models Design. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. Association for Computing Machinery, New York, NY, USA, 1807–1815. https://doi.org/10.1145/2702123.2702381
[56] 3D Potter. 2023. 3D PotterBot 10 PRO Real Clay 3D Ceramic Printer. https://3dpotter.com/printers/potterbot-10-pro
[57] Potterbot. 2023. 3D Potterbot Scara V4 Ceramic 3D Clay Printer — Real Clay 3D Ceramic Printer. https://3dpotter.com/printers/scara
[58] Narjes Pourjafarian, Fjolla Mjaku, Marion Koelle, Martin Schmitz, Jan Borchers, and Jürgen Steimle. 2023. Handheld Tools Unleashed: Mixed-Initiative Physical Sketching with a Robotic Printer. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3544548.3580691
[59] Sculpto Printers. 2023. Sculpto PRO2 3D Printer. https://sculpto-shop.com/en-us/products/sculpto-pro2-3d-printer
[60] PJRC Electronic Projects. 2023. Teensy 4.1. https://www.pjrc.com/store/teensy41.html
[61] Josef Prusa. 2023. Original Prusa MK4 3D Printer | Original Prusa 3D printers directly from Josef Prusa. https://www.prusa3d.com/product/original-prusa-i3-mk3s-3d-printer-3/
[62] David Pye. 1971. *The nature and art of workmanship.* London, Studio Vista; New York, Van Nostrand Reinhold, London. http://archive.org/details/natureartofwor00pyed
[63] Jake Robert Read, Nadya Peek, and Neil Gershenfeld. 2023. MAXL: Distributed Trajectories for Modular Motion. In *Proceedings of the 8th ACM Symposium on Computational Fabrication* (<conf-loc>, <city>New York City</city>, <state>NY</state>, <country>USA</country>, </conf-loc>) *(SCF '23)*. Association for Computing Machinery, New York, NY, USA, Article 1, 11 pages. https://doi.org/10.1145/3623263.3623362
[64] RepRap. 2023. Rostock - RepRap. https://reprap.org/wiki/Rostock
[65] Daniela Retelny and Pamela Hinds. 2016. Embedding Intentions in Drawings: How Architects Craft and Curate Drawings to Achieve Their Goals. In *Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing (CSCW '16)*. Association for Computing Machinery, New York, NY, USA, 1310–1322. https://doi.org/10.1145/2818048.2819932
[66] Alec Rivers, Ilan E. Moyer, and Frédo Durand. 2012. Position-correcting tools for 2D digital fabrication. *ACM Transactions on Graphics* 31, 4 (July 2012), 88:1–88:7. https://doi.org/10.1145/2185520.2185584
[67] Daniela K. Rosner, Miwa Ikemiya, and Tim Regan. 2015. Resisting Alignment: Code and Clay. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15)*. Association for Computing Machinery, New York, NY, USA, 181–188. https://doi.org/10.1145/2677199.2680587
[68] Valentine Roux and Caroline Jeffra. 2015. The spreading of the potter's wheel in the ancient Mediterranean. A social context-dependent phenomenon. In *The Transmission of Technical Knowledge in the Production of Ancient Mediterranean Pottery*. Austrian Archaeological Institute at the OeAW, Wien, 165–182.
[69] Roy Shilkrot, Pattie Maes, and Amit Zoran. 2014. Physical rendering with a digital airbrush. In *ACM SIGGRAPH 2014 Studio (SIGGRAPH '14)*. Association for Computing Machinery, New York, NY, USA, 1. https://doi.org/10.1145/2619195.2656328
[70] ShopBot. 2023. ShopBot Desktop. https://www.shopbottools.com/products/desktop
[71] Keith Simpson. 2023. Keith Simpson Studio. https://www.simpsonstudio.us/shop
[72] David Smith, Charles Irby, Ralph Kimball, Bill Verplank, and Eric Harslem. 1989. Designing the Star user interface (1982). (01 1989), 261–283.

[73] Min Jeong Song. 2022. Craftspeople's new identity: The impact of digital fabrication technologies on craft practices. *International Journal of Technology and Design Education* 32, 4 (Sept. 2022), 2365–2383. https://doi.org/10.1007/s10798-021-09687-1
[74] Blair Subbaraman and Nadya Peek. 2023. 3D Printers Don't Fix Themselves: How Maintenance is Part of Digital Fabrication. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference* (<conf-loc>, <city>Pittsburgh</city>, <state>PA</state>, <country>USA</country>, </conf-loc>) *(DIS '23)*. Association for Computing Machinery, New York, NY, USA, 2050–2065. https://doi.org/10.1145/3563657.3595991
[75] Rundong Tian and Eric Paulos. 2021. Adroid: Augmenting Hands-on Making with a Collaborative Robot. In *The 34th Annual ACM Symposium on User Interface Software and Technology (UIST '21)*. Association for Computing Machinery, New York, NY, USA, 270–281. https://doi.org/10.1145/3472749.3474749
[76] Rundong Tian, Vedant Saran, Mareike Kritzler, Florian Michahelles, and Eric Paulos. 2019. Turn-by-Wire: Computationally Mediated Physical Fabrication. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology (UIST '19)*. Association for Computing Machinery, New York, NY, USA, 713–725. https://doi.org/10.1145/3332165.3347918
[77] Rundong Tian, Sarah Sterman, Ethan Chiou, Jeremy Warner, and Eric Paulos. 2018. MatchSticks: Woodworking through Improvisational Digital Fabrication. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173723
[78] Timea Tihanyi. 2020. Textile Traditions. https://www.timeatihanyi.com/textile-traditions Publication Title: Timea Tihanyi.
[79] Hannah Twigg-Smith, Jasper Tran O'Leary, and Nadya Peek. 2021. Tools, Tricks, and Hacks: Exploring Novel Digital Fabrication Workflows on #PlotterTwitter. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3411764.3445653
[80] UltiMaker. 2023. UltiMaker S5. https://ultimaker.com/3d-printers/s-series/ultimaker-s5/
[81] Unfold Design Studio. 2009. Ceramic 3d Printing. http://unfold.be/pages/ceramic-3d-printing.html Publication Title: Unfold Design Studio.
[82] Joshua Vasquez, Hannah Twigg-Smith, Jasper Tran O'Leary, and Nadya Peek. 2020. Jubilee: An Extensible Machine for Multi-tool Fabrication. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376425
[83] Vormvrij. 2023. the Lutum - VormVrij 3D ceramics. https://vormvrij.nl/lutum/
[84] Ludwig Wilhelm Wall, Alec Jacobson, Daniel Vogel, and Oliver Schneider. 2021. Scrappy: Using Scrap Material as Infill to Make Fabrication More Sustainable. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3411764.3445187
[85] Wasp. 2023. Delta WASP Clay 3D printer. https://www.3dwasp.com/en/clay-3d-printer-delta-wasp-2040-clay/
[86] WAZER. 2023. Wazer Desktop Water Jet Cutter. https://wazer.com/product/
[87] Karl D.D. Willis, Cheng Xu, Kuan-Ju Wu, Golan Levin, and Mark D. Gross. 2010. Interactive fabrication: new interfaces for digital fabrication. In *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction (TEI '11)*. Association for Computing Machinery, New York, NY, USA, 69–72. https://doi.org/10.1145/1935701.1935716
[88] Junichi Yamaoka and Yasuaki Kakehi. 2013. dePENd: augmented handwriting system using ferromagnetism of a ballpoint pen. In *Proceedings of the 26th annual ACM symposium on User interface software and technology (UIST '13)*. Association for Computing Machinery, New York, NY, USA, 203–210. https://doi.org/10.1145/2501988.2502017
[89] Amanda K. Yung, Zhiyuan Li, and Daniel Ashbrook. 2018. Printy3D: in-situ tangible three-dimensional design for augmented fabrication. In *Proceedings of the 17th ACM Conference on Interaction Design and Children (IDC '18)*. Association for Computing Machinery, New York, NY, USA, 181–194. https://doi.org/10.1145/3202185.3202751
[90] Clement Zheng, Bo Han, Xin Liu, Laura Devendorf, Hans Tan, and Ching Chiuan Yen. 2023. Crafting Interactive Circuits on Glazed Ceramic Ware. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–18. https://doi.org/10.1145/3544548.3580836
[91] John Zimmerman, Jodi Forlizzi, and Shelley Evenson. 2007. Research through design as a method for interaction design research in HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '07*. ACM Press, San Jose, California, USA, 493–502. https://doi.org/10.1145/1240624.1240704
[92] Amit Zoran and Leah Buechley. 2013. Hybrid Reassemblage: An Exploration of Craft, Digital Fabrication and Artifact Uniqueness. *Leonardo* 46, 1 (Feb. 2013), 4–10. https://doi.org/10.1162/LEON_a_00477
[93] Amit Zoran and Joseph A. Paradiso. 2013. FreeD: A Freehand Digital Sculpting Tool. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 2613–2616. https://doi.org/10.1145/2470654.2481361 event-place: Paris, France.
[94] Amit Zoran, Roy Shilkrot, Pragun Goyal, Pattie Maes, and Joseph A. Paradiso. 2014. The Wise Chisel: The Rise of the Smart Handheld Tool. *IEEE Pervasive Computing* 13, 3 (July 2014), 48–57. https://doi.org/10.1109/MPRV.2014.59 Conference Name: IEEE Pervasive Computing.

A PHYSICAL UI IMPLEMENTATION

Here we provide additional details on the implementation of the Physical UI. The foot pedal and the extrusion knob are both potentiometer-based inputs that are read by an on-chip analog-to-digital converter and generate motion streams by controlling the rate of velocity-based step generators. When patched to the wheel and extruder inputs of the machine controller, for example, these motion streams result in smooth movement at a rate proportional to their respective control settings. The baby stepping knob is a low-count quadrature encoder that is read over an i2c interface. Each tick of the encoder knob increments or decrements the target position of its output channel by a fixed amount, generating a train of step pulses at a velocity-limited rate. When patched into the Z-axis input on the machine controller, this resulting motion stream causes the Z-axis to move upwards or downwards a fixed increment at a certain pre-set velocity. Lastly, the hand lever consists of a high-resolution (20,000 pulse/rev) optical encoder mounted inside a custom aluminum hub. An 8" steel lever arm projects from this hub, and terminates in a knurled aluminum handle. The encoder is monitored by a hardware peripheral inside the Teensy MCU, and even the slightest motion of the lever is registered and used to update the target position of an output channel. When the resulting motion steam is patched into the machine controller, the lever can be used to control the position of the arm directly and with low latency. Although we considered other control inputs such as a typical jog knob, the correspondence between the swinging hand lever and the swinging arm made this style of input a natural choice. While the default correspondence between the angular motion of the lever and the print arm is approximately 1:1, the display and knob interface on the module PCB allows for the sensitivity of the lever to be changed, effectively zooming in or out on the window of control.