

Exploring Texture-Level Creative Decisions with penPal, a Novel Handheld Actuated Drawing Tool

Tucker Rae-Grant
Computer Science
University of Chicago
Chicago, Illinois, USA
raegrant@uchicago.edu

Luke Jimenez
University of Chicago
Chicago, Illinois, USA
lukejimenez@uchicago.edu

Lea Albaugh
Human-Computer
Interaction Institute
Carnegie Mellon University
Pittsburgh, Pennsylvania
USA
lea@andrew.cmu.edu

Ken Nakagaki
University of Chicago
Chicago, Illinois, USA
knakagaki@uchicago.edu

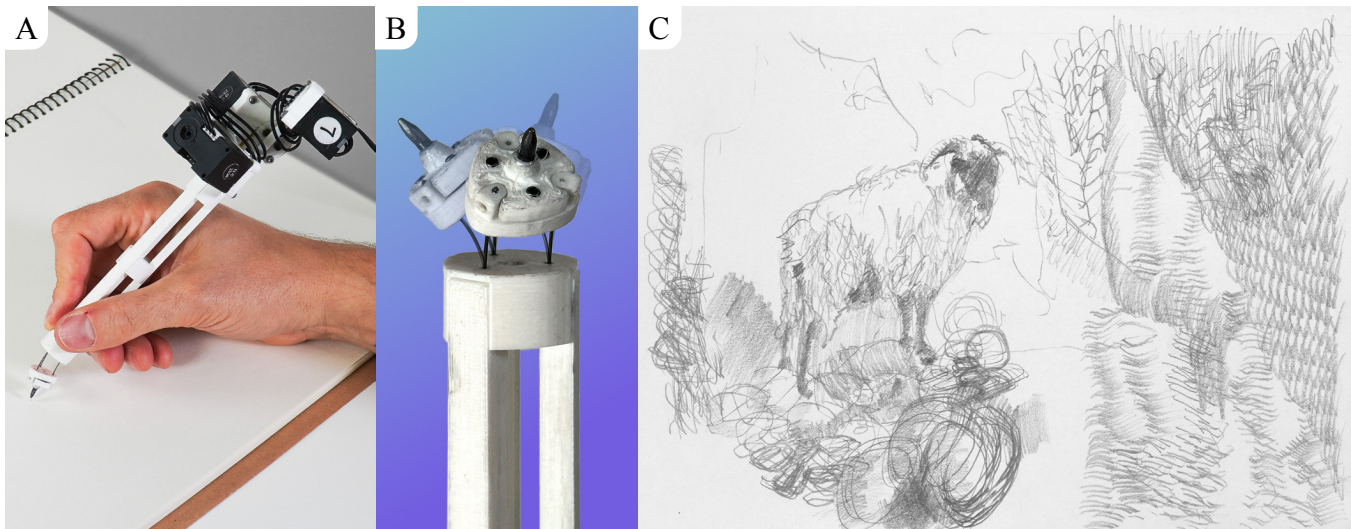


Figure 1: A) *penPal* in a user's hand. B) An illustration of *penPal* in motion. C) A *penPal* drawing made during our study (P8).

Abstract

This paper looks at texture—middle-level components—as an important aspect of drawing. We present a hardware tool, *penPal*, that is designed to support dynamic mark-making and direct creative actions at this level. By incorporating a tendon-driven continuum robot, *penPal*'s tip can move independently, giving the user a new axis of creative control. Combined with the user's own manipulations, *penPal* allows for emergent combinations of computer and manual control over the rapid generation of diverse textures. Through a 10-participant study and a professional artist commission, we examine how users negotiate control by integrating multiple coordinate systems (their body, the paper, and *penPal*'s tip) as they construct compositions. We suggest some benefits of supporting users at the texture level, such as the ability to shift the primary focus of their activity, the ability to selectively defamiliarize the creative process for generative potential, and for pleasure.

CCS Concepts

• **Human-centered computing** → **Human computer interaction (HCI)**.

Keywords

handheld tools, sketching, drawing, texture, artists, fabrication

ACM Reference Format:

Tucker Rae-Grant, Luke Jimenez, Lea Albaugh, and Ken Nakagaki. 2026. Exploring Texture-Level Creative Decisions with *penPal*, a Novel Handheld Actuated Drawing Tool. In *Proceedings of the 2026 CHI Conference on Human Factors in Computing Systems (CHI '26)*, April 13–17, 2026, Barcelona, Spain. ACM, New York, NY, USA, 16 pages. <https://doi.org/10.1145/3772318.3790391>

1 Introduction

Drawing has deep roots in human creativity, and technologies for drawing have been remarkably stable: the oldest known drawing has been dated to 73,000 years ago, and it was likely made using an earth pigment crayon similar to the pastels that are widely available today [33, 55]. Children around the world learn to draw with crayons, sticks, brushes, and markers that are often not substantially different from the ones used by expert artists. The creative expressivity of a common pencil is vast, and artists can continue to develop their skills with one for their entire lives.



This work is licensed under a Creative Commons Attribution 4.0 International License. *CHI '26, Barcelona, Spain*

© 2026 Copyright held by the owner/author(s).
ACM ISBN 979-8-4007-2278-3/26/04
<https://doi.org/10.1145/3772318.3790391>

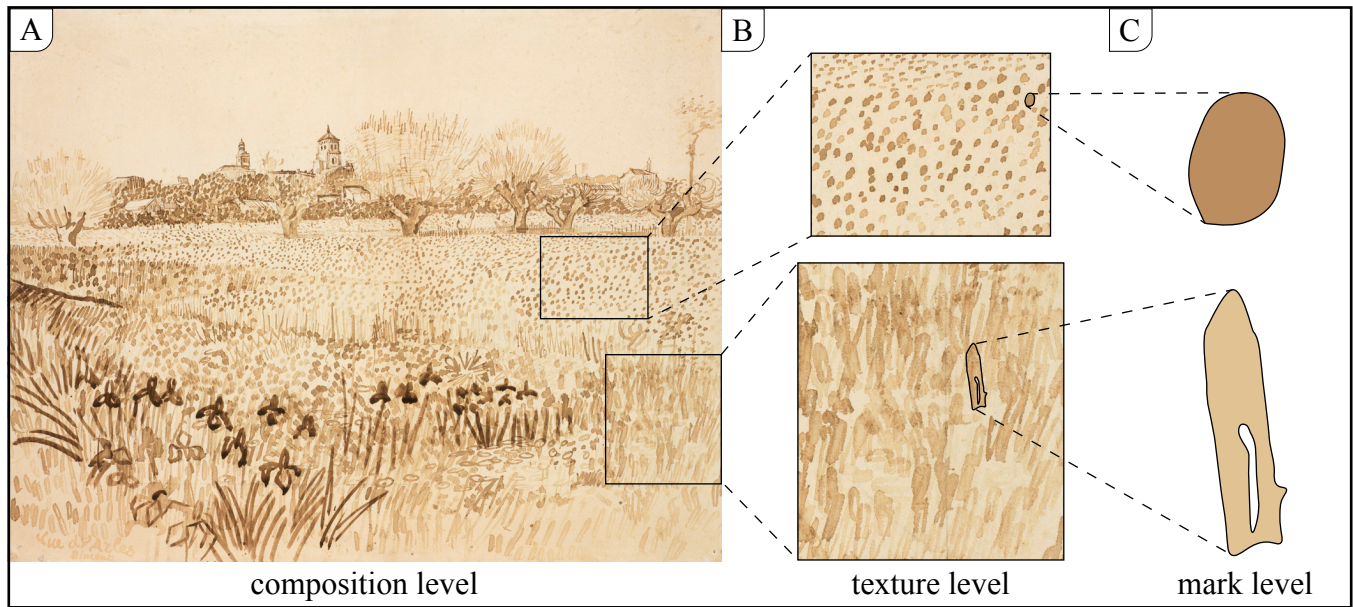


Figure 2: A) The overall composition of Vincent van Gogh’s drawing, *View of Arles* (1888) [88]; B) Texture-level areas formed of aggregate marks; C) Individual mark-level strokes.

Digital drawing tools introduce reconfigurability and speed to the drawing process and can retain the capacity for skill development, but for the most part they exist parallel to physical drawing. Additionally, an increasing number of computational systems simplify the act of creating an image to the writing a short prompt [1, 13, 30, 64], but processes such as these reduce ownership and have predetermined expressive range [36]. These latter examples also ignore the role that the act of drawing itself plays in developing visual ideas [21], and they are disconnected from our wealth of experience with physical drawing. With physical tools, users can act directly without needing to specify their action in words or numbers and can immediately incorporate real-world dimensions and material properties [58]. With this in mind, we wonder what possibilities exist for integrating the speed and reconfigurability of digital drawing tools into established and familiar physical media without eroding their directness and expressive range.

We take inspiration from Mahler, et al.’s call to “[meet] artists in their natural world” to develop a system whose computational participation in the creative process can be modulated in a way that leverages user’s embodied skills in an intuitive and immediate manner [54]. In particular, we focus on the importance of *marks* and *texture* in drawing. We use “mark” to refer to low-level individual strokes or dots, and “texture” to refer to aggregate groupings of marks that convey information about differences in form, movement, material, or abstract qualities through both the shapes of the individual marks and their relations to each other [43]. For example, in his sketch of Arles from 1888, Vincent van Gogh (1853-1890) used dots and strokes of varying lengths to develop a texture that represents a grassy field with irises, Figure 2A. As we use the term, drawn texture has two defining properties: that it is an aggregation of smaller marks, and that (in a finished drawing) it is a local

property of an overall larger composition. Texture can therefore be seen as a *middle-level element* of the drawing that sits between the lower-level marks and the higher-level composition.

In physical drawing, these levels are linked to physical scales: small marks are made with finger- and wrist-scale movements, whereas compositions frequently involve moving the arm or even the entire body. Because texture-based drawings are developed from *many* smaller marks, the underlying individual marks are often made quickly, in a cognitively automatic way. An artist using traditional tools, therefore, fluidly switches between varying physical scales and tempos as they iteratively develop the mark, texture, and composition levels of a drawing [76].

This observation led us to develop *penPal*, a novel actuated drawing tool that offers rapid computational mark-making within a handheld form factor to support dynamic, tacit transitions between levels of drawing. *penPal*’s pen-shaped body has a tendon-driven continuum robot (TDCR) which can move the drawing tip independently within a 31 mm x 31 mm square area— perfectly suited from the mark into the texture levels. Its tip motion can be controlled by an offboard GUI, and as a handheld tool, *penPal* can also be directly manipulated by its user at any of the physical scales of drawing. The simultaneous computational motion of *penPal* and tacit control from the user’s hand combine to generate a wide variety of textures, fluidly negotiated. Because the drawing tips are modular, *penPal* can be used with multiple drawing media, and it does not require an instrumented work area or special drawing paper.

We deployed *penPal* in 1) an exploratory study combining drawing tasks and semi-structured interviews with ten participants who had varied drawing experience, 2) in a demonstrational case study with a professional artist. Our findings in these studies engage

ongoing conversations about human-machine co-creation, negotiated control, and creative ownership, and bridge these to artistic understandings of tools as tacit extensions of the body. We additionally explore how familiar and selectively defamiliarized tools can leverage expertise while supporting novel creative exploration. Finally, we discuss how fluid transitions between levels and specific support for texture-level work foster emergent drawing strategies.

In this paper, we contribute:

- (1) an art-informed understanding of drawn texture as a key middle-level property for driving the design of physical tools for computational creativity.
- (2) *penPal*, a novel handheld drawing tool with a tendon-driven continuum robot working end, together with a GUI software tool to control its actuated tip.
- (3) A N=10 user study exploring how participants negotiate scale transitions and texture while drawing with *penPal*, and a follow-up interview with a professional artist to better understand how *penPal* might fit into existing studio practices.
- (4) Discussion about how augmented handheld tools can support creative exploration through negotiated control, selective defamiliarization, and intuitive level transitions.

2 Background and Related Work

In this section, we provide background on the artistic practice of drawing and discuss related work on drawing, texture, and actuated handheld tools in Human-Computer Interaction (HCI).

2.1 Sketching Input

Much HCI work has derived from a legacy of mechanical drawing (a.k.a. “drafting”) as a formal specification, especially for the machining processes that motivated early work in computer-aided design (CAD). Sutherland concluded the presentation of *Sketchpad* in 1963 with the statement that “*It is only worthwhile to make drawings on the computer if you get something more out of the drawing than just a drawing* [80].” In this line of work, a drawing becomes an interface, and sketching serves as an intuitive input that can be computationally interpreted. For example, in Mueller, et al.’s *constructable* system, users can sketch directly onto a workpiece using one of several hand-held laser pointers, with each representing a different virtual tool [58]. The system uses real-world referents and shape templates to refine the user’s pen-strokes into laser-cutting paths for functioning mechanisms. As surveyed by Johnson, et al., such sketch-based inputs have been used broadly in HCI, especially for ideation and for quickly communicating symbolic information [41]. We share this interest in the directness and familiarity of the pen as an input device. However, where these works derive from an industrial understanding of a drawing as a specification, we build on an artistic tradition of mark-making as its own complex medium combining representation and expression within each level.

Sketching can also be used as input while retaining its expressive qualities. In *SketchPath*, Frost, et al. use a pen-on-tablet input precisely to reintroduce “gestural” qualities to clay 3D printing [27]. With *penPal*, sketching is the input as well as the output; we seek to retain the gestural immediacy of a handheld pen device, while offering computational complexity.

2.2 Drawing with Machines

A variety of interactive machines for physical drawing have been explored in HCI. Pen plotters were historically developed to support technical drawing, but their relative mechanical simplicity and ability to work with different media has made them popular for artistic experimentation [85]. In HCI research, plotters have served as a site for dynamic toolchains [86], as a platform for producing 2D embellishment beyond ink on paper, such as punch-needle embroidery [32], and as a tool for guiding novice calligraphers [22]. Rather than directly manipulating the mark-making tool, Lee and Ju experimented with the concept of an “adversarial” robotic drawing pad intended to spur human creativity by interrupting a user’s intentions [50]. These projects explicitly engage artistic practice, as we do with *penPal*.

Reinventing the plotter with novel form factors, *RoboSketch* combines a wheeled robot with a small inkjet printer and a pen-shaped joystick [66], and *COMP*PASS* plots on a polar coordinate system with the rotation driven manually by the user [60]. These projects tap the familiar interaction paradigm of tabletop drafting tools, and they are lightweight and flexible for on-the-fly interaction. *penPal* is similarly focused on a flexible and familiar interaction, but with an emphasis on expressivity and fully hand-held control.

2.3 Texture

2.3.1 Definition and Background. Texture – an aggregation of smaller marks that is a local property of an overall larger composition – is frequently used to both represent physical material texture [7, 35] and to communicate expressive qualities such as motion [17]. Physical texture is often abstracted in drawing; as one drawing textbook states, “...if you are drawing a block of wood, you do not need to copy every grain that you can see on it; you should try to *imply* the grain [emphasis in original] [76].”

Texture is often used to produce differing areas of *value* (lightness and darkness) in a drawing, for example to create the effect of lighting on a 3D form. Traditional drawing techniques for rendering value through texture include *shading*, *hatching*, and *mark-making*. All of these involve making aggregate strokes with a drawing tool. *Shading* is the use of smooth gradients, and it tends to be used with softer materials that can be manipulated by varying the pressure of the drawing tool [7]. In *hatching*, the effect of numerous parallel lines is modulated by varying the spacing between them, their weight (thickness and darkness), and their direction [34]; this technique is often used with firmer, more precise tools such as pens and hard graphite [16]. While we use “mark” to refer to any individual stroke or dot, *mark-making* specifically refers to drawing that uses more idiosyncratic marks than hatching or shading, and where the individual mark carries semantic meaning as part of a group of marks [34, 76]. We saw all three of these kinds of texture being used by a range of expert and novice participants in our study.

2.3.2 Computational Texture. Our definition of texture, as summarized above, is specific to the context of drawing. However, related meanings in graphics and HCI research suggest how our work can be applied more broadly.

In computer graphics, “texture” often refers to an image that is mapped onto a 3D form [8, 15], which implies a conceptual separability between material and shape that is not, on its face,

compatible with our inquiry into smooth transitions between mark, texture, and composition levels. However, this graphics-oriented definition of texture has influenced how creators conceptualize texture on physical objects, most notably in Faruqi, et al.'s line of inquiry into wrapping separately-generated haptic textures onto printable models [23, 24]. We see a similar alignment between the work on digital brushes described below (subsubsection 2.3.3) and our work with physical media.

Looking to HCI research, our “texture” most closely aligns with the idea of *grain* as defined by Albaugh, et al.: a mid-level property of physical materials which “emerges from its aggregate low-level properties, but which is conceptualized abstractly by skilled creators [4].” Similarly to the way that working in *grain space* lets people abstract low-level fabrication steps, *penPal* allows users to work at the middle level of texture while lower-level marks are made implicitly. This has the potential to open up new ways of being creative with drawing, as we observed in our study.

Computational fabrication support tools like *WeaveSlicer* [26], *Vespidae* [25], and *Playing the Print* [77] have explored parametric control of aggregate material texture; in particular, these three contribute to an ongoing conversation on “CAM-based” fabrication which bypasses modeling a specific output and instead directly choreographs machine toolpaths. When enacted on real materials, these parametric toolpaths create complex effects which would have been difficult to model otherwise. In the CAM-based work *Millipath*, Bourgault and Jacobs developed a parametric toolpath programming platform for developing diverse surface textures [10]. They introduce the concepts of *action*, or “the convergence of tools and materials at the moment of fabrication” to describe the unique emergent interactions of computability and materials and “design scales” to describe different levels of spatial organization and tool affordance that affect the production of texture. We see *penPal*'s hybrid handheld robotic approach as similarly producing emergent outcomes between robotic tip-paths and real-time human guidance.

2.3.3 Digital Brushes. Many mature software options exist for expressive digital drawing [2, 3, 28, 38], and many of these use an interaction metaphor of “brushes” that can add complexity and variety to user-drawn strokes. While some “brushes” emulate physical media, others are purely imaginative; either kind may be designed and modified parametrically by users, and “brush packs” may be developed, traded, and sold between artists [78]. *I/O Brush* uses this metaphor to describe a tangible tool for sampling textures from the physical world and painting with them on a screen [72], while in *CATS*, Sethapakdi, et al. apply graphics manipulation techniques to develop sampled local texture into fluid digital brushes [74]. In contrast to these photo-based method, Kazi, et al. preserved the workflow of pen-and-ink illustration when they developed *Vignette*, a vector graphics editor that synthesizes textures from user-drawn example patches within bounded areas or along paths [43].

In *Para*, Jacobs, et al. developed a system to enable parametric textural effects via direct manipulation of constraint relationships between elements, such as their distribution, size, and color variation [40]. In *Extending Manual Drawing Practices...*, the authors focus on developing the *Dynamic Brushes* system, which engages with the embodied, manual skills that artists have developed with traditional tools by centering physical data from a stylus as the

primary system input [39]. Significantly, the authors describe their system as an “environment for *personal drawing-tool creation*.”

We are inspired by the “brush” metaphor and particularly by the framing of digitally flexible personal drawing-tools. We imagine *penPal*'s interface as a means of producing ad hoc “drawing tools,” refining favorites, and developing a personal workflow, with the additional advantage that *penPal* brings these drawing tools back out into the physical world, allowing these computational brushes to be physically wielded by the artist.

2.3.4 Texture Machines. Several simple but satisfying handheld machine systems center texture production. In *Digital Rubbing*, the authors created a wireless pen with a solenoid-actuated pencil that can rapidly raise and lower the drawing tip to mimic the effect of *rubbing*, a drawing technique for transferring textures from 3D surfaces to paper [45]. Two commercial varieties of motorized pens exist: pens with eccentric rotating masses that make looping marks [84], which are mainly marketed as toys but which have also been used for their haptic feedback [42], and pens with reciprocating mechanisms that make dots [18, 37], which are found as labor-saving devices for artists who use stippling [18] and as training tools for tattoo artists, since electric tattoo machines use a similar action [37]. Each of these offers just one kind of mark, possibly with speed control. The computational artwork *Pen Wiggler* gradually approximates a provided image through stochastic motion of a brushbot pen, resulting in a randomly-textured drawing [73]. *penPal* offers specific robotic control over the marks made, providing a deep range of textural possibilities under user control.

2.4 Scale and Augmented Handheld Tools

2.4.1 Definition and Background. Physical drawings are scale-dependent. For example, different circles drawn with the same pen have different visual weights: the thickness of the pen is constant, so the ratio of stroke thickness to circle diameter changes. This is a notable difference from digital drawing, where the scale of strokes can be modified independently. Hand-drawn marks are also greatly influenced by the properties of the drawing tool and of the artist's body. Drawing tools vary in terms of hardness (how much material will be deposited on the page) as well as thickness. Thickness itself can change based on tool orientation and the shape of the tool's tip. An artist can create dots on a page by poking it with the end of a piece of charcoal, or they can turn the same piece of charcoal on its side and drag it perpendicular to its length to draw a broad, shaded area. Anatomical kinematics also determine the marks that are possible (and comfortable) to make, with noticeable effects on the textures arising from those marks. For example, most people find it easier to make rapid back-and-forth strokes by bending the wrist rather than by rotating the forearm, making shading likely to happen at angles that depend on the handedness of the artist¹.

In hand drawing, scale also affects how long a texture takes to create, which can be a practical constraint. Digital drawing systems make copying strokes effortless and generative brushes can add arbitrary complexity to strokes as they are drawn. Conversely, hand-drawn marks are made one at a time, and larger or more precise

¹As a simple experiment, try each for one minute and compare their speed and how fatiguing they are.

marks may be drawn more slowly or require additional tools (such as straight edges and stencils).

2.4.2 Action Scale in Augmented Handheld Tools. To be interactive, fabrication tools must be designed for the physical and temporal scales of the human user. While a variety of approaches to this have existed, from pottery wheels that incorporate clay 3D printers and hybrid functions [57] to robotic arms that can be manually trained to elaborate on marks made by users [9], we focus here on handheld form factors because they enable the possibility of simultaneous control and a very direct override. As Zoran, et al. outline in *Wise Chisel...*, this handheld scale constitutes a “hybrid territory” where on-the-fly design decisions, intuitive control, and computational affordances merge in enacting an output [91].

While the size of handheld devices implies that they usually operate within arm’s reach, there is wide variation in terms of the actions available to both user and system. The interactions between system and user can be complex, so we find it helpful to think about them in terms of the levels laid out in Section 1: *mark-level*, *texture-level*, and *composition-level*. When interpreting the scale of an action, it is important to consider the two main axes that can vary on both the system’s and the user’s end: the speed and the size of motion. An action that is fast and large is likely to have a greater effect at the scale of the overall form (the composition level) than a slow and small action.

Material interactions can also affect the levels that users can work at with a particular device. While the handheld form of *FreeD V1* [90] allows users to make large motions at high speed, the device’s small cutting bit means it will be unable to remove material fast enough to make these actions effective. Consequently, users must proceed by removing small amounts of material at a time to excavate their desired form. By taking these mark-level actions, they develop texture and composition. With *dePENd* [89], on the other hand, large and fast motions performed by the user will still make marks on a piece of paper. This means that users can take independent action at all three levels.

The system and user can work simultaneously at different levels: as the user carves away with *FreeD V1*, the tool operates to ensure “model protection” at the composition level by changing the cutting bit speed and location to prevent it from entering the boundary of a 3D model virtually superimposed on the material [90]. *FreeD V2* implements additional features, allowing the tool to work simultaneously with the user at both the mark level (with its “virtual bit” function) and the texture level (with semi-autonomous texture rendering) [92]. With *dePENd*, users can optionally wiggle their hand to simultaneously address the texture level while following the system’s composition-level guidance [89]. *Phasking on the Paper*, which also offers drawing guidance in a handheld device, allows users to negotiate composition-level paths with the system [44].

Similarly to *dePENd*, users can independently draw with *penPal* at all three levels by turning of the motion of its tip. While the tip is in motion, they can flexibly shift between acting simultaneously at the mark and texture levels with the tool, or *penPal*’s motion can contribute to lower level strokes while the user draws composition elements, as we will discuss further in Section 6.3.

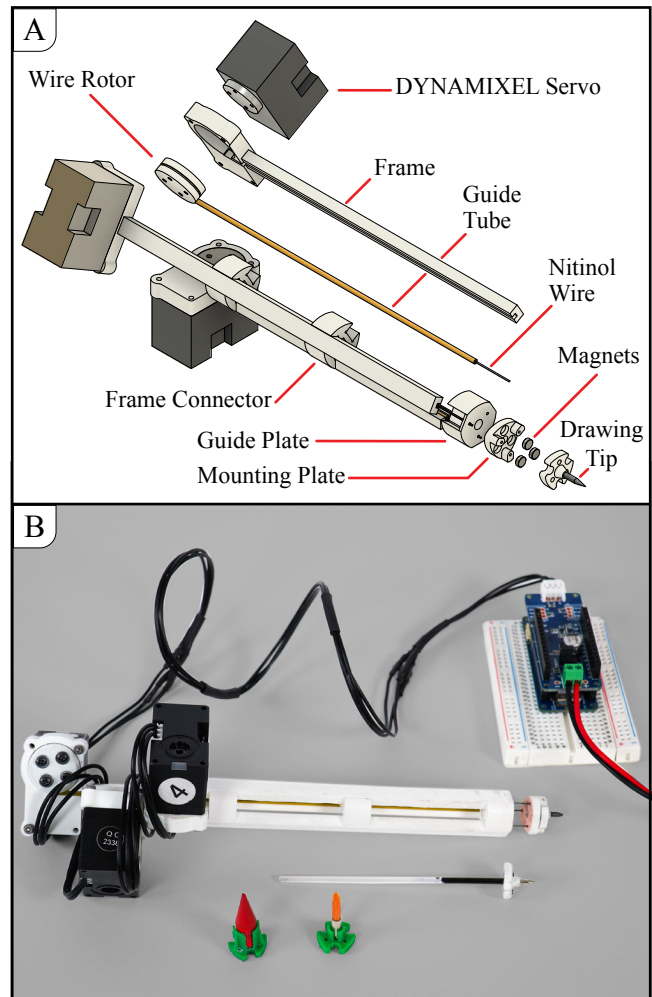


Figure 3: A) *penPal* is composed of 3 snap-together, printed frames that hold the motion platform. As each servo turns its rotor, the attached nitinol wire spools or unspools, changing the length of wire extending from the end. Because the three wires are connected to the same mounting plate, their coordinated movement can create translation and bending moments at the drawing tip; B) The *penPal* system including microcontroller and a variety of drawing tips.

3 Implementation

At its core, *penPal* is a pen-shaped, handheld device with a tendon-driven continuum robot that can rapidly move its drawing tip within a 31 mm x 31 mm square area. *penPal*’s embedded system is commanded by a graphical user interface (GUI) built in Processing, which can run in both wired and wireless configurations.

3.1 Hardware

While pens, pencils, and other drawing implements exist in a broad design space, the majority of examples are utilitarian and fall within a narrow range of form factors, usually between 7 mm and 14 mm in diameter, from 120 mm to 200 mm in length, and hexagonal or

round [63, 81–83]. From an early age, people are taught how to hold and use these implements [52], and because of the fine motor skills and repetitive motions involved, awkward hand positioning or designs that significantly deviate from the norm can negatively impact joint and tendon health [75]. With this in mind, we designed *penPal* to conform to the norm as closely as possible so that users can focus on the act of drawing.

penPal consists of a modular 3D-printed PLA body that supports the motion system and affords users a familiar grip (see Fig. 3). The open form creates natural resting spots for the fingers, and the diameter of the virtual circle described by the three contact points is 14.4 mm. The weight of *penPal* is 98.4 g, half of which is due to the motors. The main consideration for creating a tool with the same form as a typical pen or pencil was the location of the motors. We opted to use Bowden cables to transfer force from rotary motors that are positioned away from the tip, allowing for an unobstructed handle and working end.

The motion system is driven by three servomotors (Robotix DYNAMIXEL XL330-M288-T [70]), which have wire rotors attached to their outputs. When rotated, the servos push or pull their attached superelastic nitinol wires [62] through a length of plastic tubing running along each edge of *penPal*. An earlier version used braided steel cables [67], but the repeated bending around the rotor led to fatigue failure after two months of testing, and there was visible deformation of the cables near the drawing tip. The superelastic nitinol has not exhibited the same deformation, and the first fatigue-related failure occurred after six months of use. On the rotor end, each wire is pressed into a rounded slot that holds the wire in place through friction, allowing for easy replacement. At the working end, the wires are permanently glued into a shared mounting plate which has three neodymium magnets and stabilizing posts to provide a secure attachment point for interchangeable tools. These tools, which include 2 mm diameter graphite leads, multiple colors of ballpoint pen, 7.4 mm colored pencils, and a paintbrush, are fixed into printed plates with removable steel pins that mate with the magnets on the mounting plate (see Fig. 3B for the complete system).

The three wires comprise a tendon-driven continuum robot (TDCR). As the servos rotate to different positions, the length of wire extending past the body changes. If all three wires move the same distance at the same speed, then the mounting plate moves in a linear path away from or towards the end of the device. If the wires change their lengths different amounts, however, they induce bending in each other due to their shared mounting point. The coordinated motion of the three cables allows the end effector to bend in two axes (X,Y) and to translate along a third (Z). This allows the drawing tip to travel to positions within a “pointed triangular dome” working volume of approximately 40 cm³ when not limited in software to a range optimized for speed and stiffness, as illustrated in Figure 5. Through computation control of the servo positions, described below, the motion of the tool tip can be guided between arbitrary points within this volume.

Various other compact motion platforms for handheld tools exist, including 3-degree of freedom parallel manipulators [53, 90, 92], small delta robots [56], and concentric tube robots (CTRs) [29, 79]. The smallest of these use piezoelectric actuators for their compact size and high bandwidth, resulting in operating frequencies of 75 Hz or more [53, 56]. Due to their high cost and small ranges

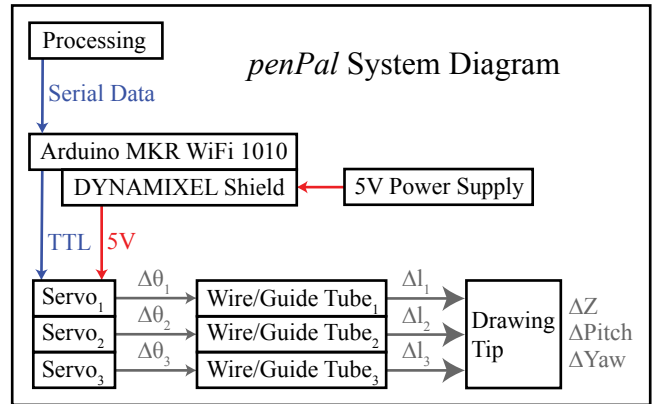


Figure 4: The electronics of *penPal* are relatively simple, with an Arduino microcontroller receiving serial commands from the Processing GUI and sending them through a DYNAMIXEL shield, which also supplies power to the three motors. The motors work in parallel to effect motion at the drawing tip.

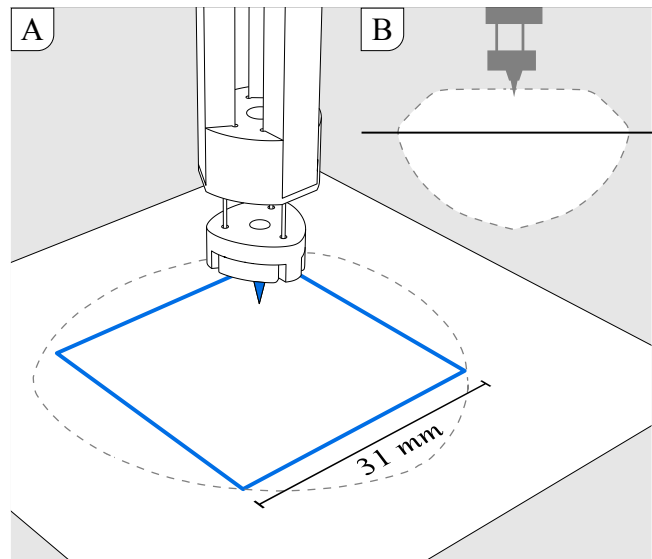


Figure 5: Relative to the main body, the tip of *penPal* can reach a three-dimensional space constrained by its three-wire control. Our interface software presents a simplified square bounding box with the drawing plane positioned at the widest part of the drawable volume at the largest drawing area. A) The blue line represents the largest square that can be produced within our GUI interface; it is 31 x 31 mm. B) A side view of the reachable area showing a drawing plane positioned at the largest drawing area.

of motion, piezoelectric actuators were not a good candidate for *penPal*. While the compact CTR design presented in Girerd and Morimoto is handheld, it is mechanically complex and its form is not suited for a pen-shaped device. Zoran’s et al.’s *FreeD V2* design is the most similar to *penPal*’s, but employs bar linkages instead of

cables [92]. While this design could be miniaturized, we suspect that reducing the diameter of the handle would limit the range of motion in the X and Y axes because the linkages require internal clearance to pivot. Additionally, *FreeD V2* is optimized for use with a rotary carving tool, which contains a powerful spindle. Consequently, when making 3D motions, its entire motion platform moves relative to the sleeve held by the user. With *penPal*'s rapid motions, this would generate significant, disruptive shaking. Because it uses tendons and the mounting plate and drawing tip weigh 1.54 g combined, these inertial forces are largely irrelevant. In addition to affording a compact form, wide range of motion for the given task, and a remote location that leaves the handle unobstructed, the use of a TDCR had an additional benefit: because the wires are unsupported past the pen body, they introduce a small amount of natural compliance in the drawing tip (see [12] for a similar construction in a Gough Platform configuration). Combined with the compliance and light downward force provided by the user's hand, this reduces the amount of precision required from the user and system to maintain contact with the paper, allowing us to forego the position tracking present in *FreeD* [90, 92].

The total cost for our system, excluding the external power supply, was approximately \$150 (USD) at the time of writing.

3.2 Software Implementation

penPal is controlled by an Arduino MKR WiFi 1010 microcontroller (MCU) with a Robotis DYNAMIXEL shield [69]. The C++ program running on the Arduino initializes the servos, which have their own embedded MCUs, and operates as a server translating commands between the Processing GUI and the motors. All communication is handled via serial communication (see Fig. 4).

Users set the motion with a companion GUI (see Fig. 6), which we have implemented in Processing (Java) on both computers running macOS and on Android tablets. The GUI allows users to select from four preset motion paths or to draw their own custom paths. They can adjust the speed, size, and rotation angle of the chosen path. In its prototype form, the GUI incorporates simple “save” and “load” functions for storing user-created motion paths (See Fig. 6). Inspired by Levin's *Yellowtail* [51], we sample points as they are drawn according to their position and time. By playing through these points according to their timestamp, the strokes retain their relative speed within the stroke. Because some pilot users found this unintuitive, we added a “normalize” button which replays the strokes at a constant speed. If the first and last points of the user-drawn path are less than 2 mm apart, the program will automatically close the ends and follow a loop-wise motion. Otherwise, it traces back-and-forth across the path.

We use two different methods for translating between the 2D motion paths in the GUI and the rotational positions of the three motors. The empirical method, which was used to control *penPal* during the user study, utilizes a lookup-table (LUT) relating grid positions to each of the motors' rotational positions. We derived this LUT by mounting *penPal* above a 36 point, 25.4 mm² grid, manually commanding the tip to each of the points, recording the three servo positions required to reach each point. We fit a polynomial regression to the data set matching XY coordinates to servo positions, and we generated a servo position LUT for XY

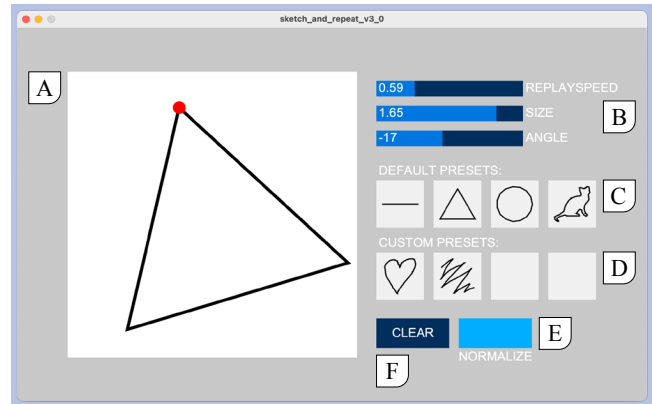


Figure 6: This graphic interface, made in Processing using the ControlP5 library, provides simple control over the motion of *penPal*'s tip. The Cartesian coordinates of the red tracking dot are converted to angular servo positions, which are sent to *penPal* over a serial port. A) Drawing Input Area/Display Window; B) Output Parameters; C) Default Presets; D) Custom Presets; E) Normalize Button; F) Clear Button.

positions in 0.5mm increments. In this case, we selected a plane approximately 1 cm away from the fully retracted graphite tip since this gave us a range of motion well-suited to making rapid textures.

This empirical method was sufficiently fast and accurate for running our study, but does not take full advantage of the degrees of freedom of the TDCR. Rather, it limits *penPal*'s output to one plane. To address this for future improvements, we developed an ad hoc mathematical model of *penPal*'s TDCR that allows us to target any point in its workspace (see Supplementary Materials: Model). In the future, this could be supplemented with an IMU to allow *penPal* to maintain contact with a surface while being tilted.

The key assumption underlying the model is that, because the bending forces are distributed equally throughout the lengths of the wires, they form arcs under non-extreme conditions. Furthermore, the tendons are constrained and arranged equally at both ends and meet the guide plate and mounting plate at right angles. Therefore, we assume that each tendon bends about some shared central axis, and thus their collective form is equivalent to revolving the triangle at their base, from which the tendons extend, about this rotational axis and by some angle θ . We want to know where this base triangle's vertices will end up after their revolution, which we found using Rodrigues' rotation formula [71]. From there, for some given point, we can compute an axis and θ which will bring the tip there and in turn find tendon lengths and motor commands to realize that position with *penPal*.

4 Drawing with *penPal*

4.1 User Study Methodology

To evaluate how users navigate scale transitions and explore texture, we conducted a study with 10 adult participants consisting of a series of drawing-related activities interleaved with semi-structured interview questions. These activities were intended to balance task-oriented and open-ended engagements with *penPal* so that we could

	Drawing Experience	Formal Training	Typical Drawing
P1	3	2	Digital drawings from imagination using an iPad, stylus, and Procreate.
P2	3	2	Representational drawing using charcoal, pencils, and markers.
P3	3	3	Abstract drawings using pens, pencils, and tracing paper.
P4	1	2	Drawings from observation using permanent markers.
P5	2	2	CAD drawings for work.
P6	2	1	Digital drawings using an iPad to create logos and game assets.
P7	2	1	CAD or graph paper for work, stream-of-conscious sketches using pencils, pens, and markers for fun.
P8	3	3	Recently has mostly been drawing with pens in order to design three-dimensional artwork.
P9	2	1	Cartoons, portraits, and simple pencil sketches for painting over with watercolors.
P10	1	1	Flowers drawn from imagination using pen.

Table 1: We quantized participants’ backgrounds on a 3-point scale. For Drawing Experience, 1 reflects to statements like, “I don’t draw very much (P10),” and 3 to statements like, “I’ve been drawing for most of my life (P1).” For Formal Training, 1 was assigned to those with no training outside of mandatory school art classes, and 3 to people with specialized training.

observe its use in a variety of situations within a short period of time. Participants were recruited directly and their self-reported drawing experiences ranged from formal academic training with almost daily practice to never having received drawing instruction and rarely drawing (see Table 1). We selected participants with this range of experiences to see if there were significant differences in how people wanted to use *penPal* and perceived its affordances.

The study had three sections: an introduction, drawing activities with *penPal*, and an exit interview, and lasted from 60 to 105 minutes (see Supplementary Materials: Detailed Protocol for the complete description). Audio and video recordings were made with the consent of the participants. The audio was auto-transcribed locally with *Whisper* and manually corrected [68]. Participants’ drawings were collected and scanned, and participants could opt to have them returned later. This study was approved by the review board of the University of Chicago (IRB125-1031). Participants were compensated with a \$20 gift card at the conclusion of the study.

4.1.1 Introduction. The introduction consisted of an intake interview and a warm-up exercise. Participants were asked to describe their drawing experience, including how often they draw, what their drawing practices usually entail, and whether they have ever taken formal drawing classes. Particular attention was paid to the tools that each person normally uses, why they like them, and whether or not they ever modify them.

The warm-up was designed to build rapport and establish some shared language for describing the visual qualities of lines and patterns. During the first portion, participants looked at three swatches taken from an ink drawing by Vincent van Gogh (See Supplementary Materials: Detailed Protocol: Warm-Up) [87]. They were asked to describe the hand motions that an artist might make with a tool to create each set of marks. The goal of this was to encourage participants to imagine a range of possible manual control strategies before they were introduced to *penPal*. Next, they were shown three printed textures (See Supplementary Materials: Detailed Protocol: Warm-Up 2) and were instructed to draw a pattern to represent each one using a standard pencil. They were asked about how they came up with the patterns that they drew, what they liked or disliked about them, and what they would do differently given more time.

4.1.2 Drawing Tasks with *penPal*. The drawing tasks were designed to encourage varied exploration with *penPal*. After a brief demonstration of the system, participants were given 5 minutes to freely explore *penPal* by drawing in a sketchbook. Afterwards, everyone was asked about their initial impressions and what they liked or disliked about their doodles².

For the first structured task with *penPal*, participants were asked to shade in the outlines of a cube and a cone printed with dashed lines below examples of a cube and a cone evenly shaded in grayscale (See Supplementary Materials: Detailed Protocol: Task 2 (shading)). They were told they could shade as many as they wanted, but needed to do at least one of each. Whenever participants asked for clarification, they were told they could interpret “shade in” however they liked and that the examples were simply provided as inspiration. Afterwards, they were asked a series of questions to establish their process and rationale, such as “How did you decide which motion to use for the cube?” These were supplemented with questions based on the interviewer’s observations.

Before the final drawing activity with *penPal*, participants were shown a digital image of Vincent van Gogh’s drawing, *View of Arles* (1888) (see Fig. 2A) [88]. After being instructed to describe some of the ways the artist used different marks, they were asked which parts, if any, they thought could be made with *penPal*. Following this, they were given ten minutes to draw whatever they wanted. To reduce the potential stress of choosing a subject, three **optional** references were provided. After completing their drawings, they were asked another series of questions; this time focusing on their experiences of mastery, fun, difficulty, stress, and enjoyment.

4.1.3 Questionnaire and Exit Interview. At the end of their session, each participant completed a brief 5 question, 5-point scale Likert questionnaire whose purpose was to prime them for the discussion, rather than to collect vital data. During the exit interview, participants were asked questions based on their specific activities during the session as well as a series of fixed questions:

²“Doodle” describes a very informal kind of drawing that may or may not have representational elements. It is frequently used to describe drawing done while simultaneously paying attention to another activity, such as a meeting.

- (1) “Imagine that *penPal* can draw things perfectly. You can use your own interpretation of “perfectly,” but one thing it might mean is that whatever appears on the screen is drawn accurately on the paper. How do you think that would that change your experience of *penPal*?”
- (2) “Did *penPal* change how you thought about the process of drawing while you were using it?”
- (3) “Did it feel like *penPal* was doing any parts of the drawing for you? If so, which ones?”
- (4) “When you had a specific task in mind (like shading in the cone), how did you decide what to have *penPal* do?”
- (5) “Was it different during the open-ended drawing periods?”
- (6) “Was there anything frustrating about drawing with *penPal*? If so, how did you feel about that frustration?”
- (7) “In these trials, your control over the motions of *penPal* were fairly limited. After using it for a while, what do you wish you could control about it? What do you wish it could do?”

5 Participant Experiences

Our study provided rich feedback in the forms of transcripts, videos, and artwork. From the roughly 15 hours of audio, we surfaced 32 codes from 313 quotes using reflective thematic analysis and further distilled these into 13 higher-level codes [11]. Here, we describe the experiences participants had with *penPal* and we discuss themes that emerged from interviewing a professional artist.

5.1 Orienting to *penPal*

None of the participants had used *penPal* before the study, but all had used pens and pencils. Here we detail how they familiarized themselves with *penPal*, drawing on their established skills and also observing where the tool diverged from traditional ones. The study gave participants undirected time to acquaint themselves with the system before they were asked to perform a task or create something purposefully artistic (see Supplementary Materials: Exploratory *penPal* Doodles). In most cases, they worked all over the provided paper, trying out a variety of different tip motions and actions with their hands. Many participants initially expected the strokes made with *penPal* to perfectly match the paths shown in the GUI. In discussing this, P9 reflected that his knowledge of robots led him to expect that *penPal* would contribute precision to his drawing experience. This discrepancy between what was on-screen and what happened on the paper was most commonly noticed with complicated paths like the **cat** preset or elaborate user-drawn ones. Describing shaking off the same preconception, P8 explained that they quickly realized that “the way that you hold this pen is never going to be inconsequential to what’s drawn.”

Because the wires that control the tip are very thin (0.5 mm), several participants were initially unsure how much pressure they could apply to *penPal*. Additionally, some worried about breaking the prototype. In these cases, we reassured participants that we wanted to learn points of failure and that they should not feel constrained in their use of it. After the exploration period, P6 remarked that, “This thing is serious! ...the fact that I can actually put some pressure on it is actually cool,” and P2 said, “...once I started to put a little pressure on it I realized that I could manually expand the

strokes or the replay speed or the size with my hand based on how I moved it across the paper, which was really fun.”

5.2 Combining System and User Motion

The shading task was intended to encourage participants to develop ways to exert control over *penPal*'s output by presenting them with a worksheet similar to ones used in elementary schools [47], where children are encouraged to color inside the printed boundary lines (see Supplementary Materials: *penPal* Shading Task). While they were not explicitly told to replicate them, almost all of the participants initially tried to match the values and shading of the examples. Many converged on using the **line** preset because it aligned with how they would shade manually. Some, like P1, relied on this back-and-forth tip motion to make the marks, using their arms to scan the tool across the front of the cube perpendicular to the direction of the tip. His scanning lines are especially visible where he rotated the paper 90° to darken it with cross-hatching (see Fig. 7B: P1). P4 similarly let *penPal* make marks, but moved his arm more slowly and in a less linear path, resulting in more even shading. P9 demonstrated another permutation of this, moving his hand in the same direction as the tip to augment the size of its motion (see Fig. 7B: P9). P5, who had requested a ballpoint tip, also let *penPal* make the marks, but used the **circle** preset and held the tool at an angle to make C-shaped marks arranged in even columns (see Fig. 7B: P5).

Some experimented more when shading additional shapes. P3, whose typical drawing style was more abstract than other participants, quickly abandoned a cross-hatching technique after filling the top of the cube and switched to using the **circle**. While *penPal*'s tip moved clockwise, she moved her wrist counter-clockwise to create chaotic loops. After completing the cone, where she commanded *penPal* to make large C-shaped marks to match the shape of the base, P2 began exploring bands of different textures on the face of the second cube (see Fig. 7B: P2). On reflection, she said, “I really just enjoy how many textures... it’s just really interesting mark-making. It’s just a little landscape inside a cube!” It is worth noting that these two participants each decided to spend approximately 30 minutes on this task, and we will discuss this exploratory (as opposed to goal-oriented) behavior in Section 6 below.

5.2.1 Adjusting Grip. Participants experimented broadly with *penPal*, as shown by the wide variety of grips they used to find different effects. While we observed many variations (see Supplementary Materials: *penPal* Observed Grips), most can be described as:

- (1) **Low** (see Fig. 8A), which was used for fine control. This included anchoring their hand to precisely combine wrist and tip motions and using *penPal* to draw mark-level details.
- (2) **Middle** (see Fig. 8C), which was used to increase variation in the marks, to draw texture-level fills, and to “extend” *penPal*'s motion (P1). P6 combined this grip with the **circle** preset and an up-and-down motion to randomize the location of the dots in his final drawing (Fig. 7C, P6).
- (3) **High** (see Supplementary Materials: *penPal* Observed Grips), which was used for fast, composition-level lines and to allow the participant to feel like *penPal* was exerting more control. P3 combined this grip with the **cat** preset while outlining a cone (see Fig. 7B, P3, left).

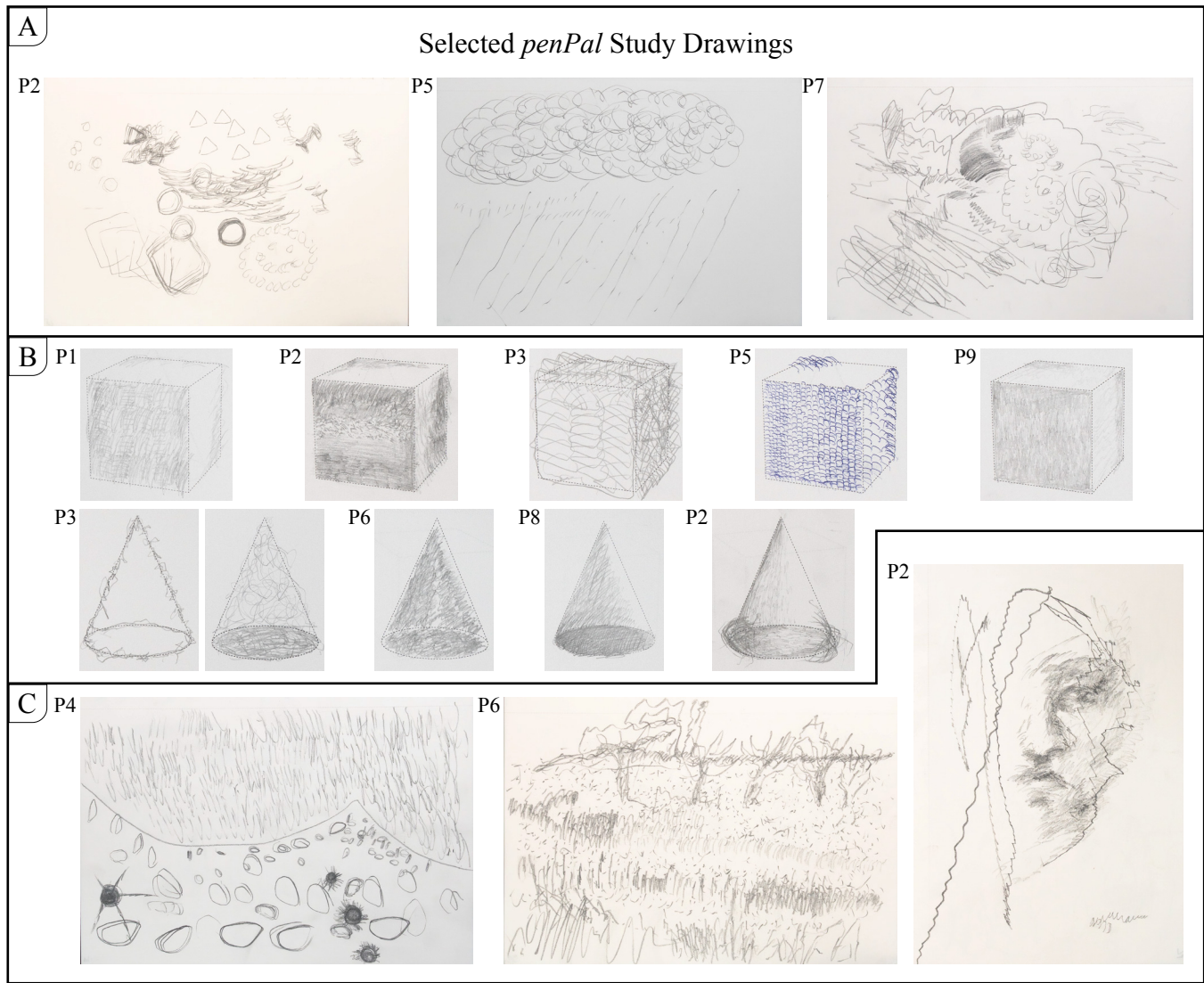


Figure 7: A selection of drawing results from our 10-participant user study. The complete set of drawings can be found in the Supplementary Materials. A) Results from the initial 5-minute exploration period. B) Shaded cubes and cones demonstrating a wide range of texture-level fills. C) Results from the 10-minute open-ended drawing, showing discrete, parametrically adjusted shapes (left), mark-based texture-level areas (middle), and a value-based drawing with composition-level lines (right).

Another notable grip we observed was an “Ouija³” grip with *penPal* resting loosely between the thumb and index finger. P3 tried this during the initial exposure phase and said that she wanted, “...to see if *penPal* could take my hand everywhere.” This represents one of several early attempts by participants to find composition-level guidance in the tool, but we do not claim this as a feature of *penPal*.

³Ouija is the trade name for a game in which multiple participants jointly control the motion of special pointer sitting on a board with alphanumeric characters printed on it. The conceit of the game is that spirits control the motion of the pointer, and players often claim they have *not* moved it as it spells out words. Here, we use the term to reflect P3’s feeling that *penPal* was moving on its own [31].

5.3 Ongoing Discovery: Case Study

Most participants’ use of *penPal* evolved during their session. As a case study, we describe P8’s end-to-end process for their final drawing (see Fig. 8) where they made several discoveries for new ways to use *penPal*. Following the shading task, P8 asked for and was given a longer piece of graphite, which they modified to be 3 cm long with a sharp point. This reflected how their training had taught them to prepare pencils. With the tip motion stopped, P8 used *penPal* like a traditional pencil for 2 minutes to outline the sheep and shade its face and legs (Fig. 8A). Next, they replicated the fleecelike mark they created during the warm-up (See Supplementary Materials: *penPal* Texture Warm-Up: P8 and Fig. 8B) and allowed

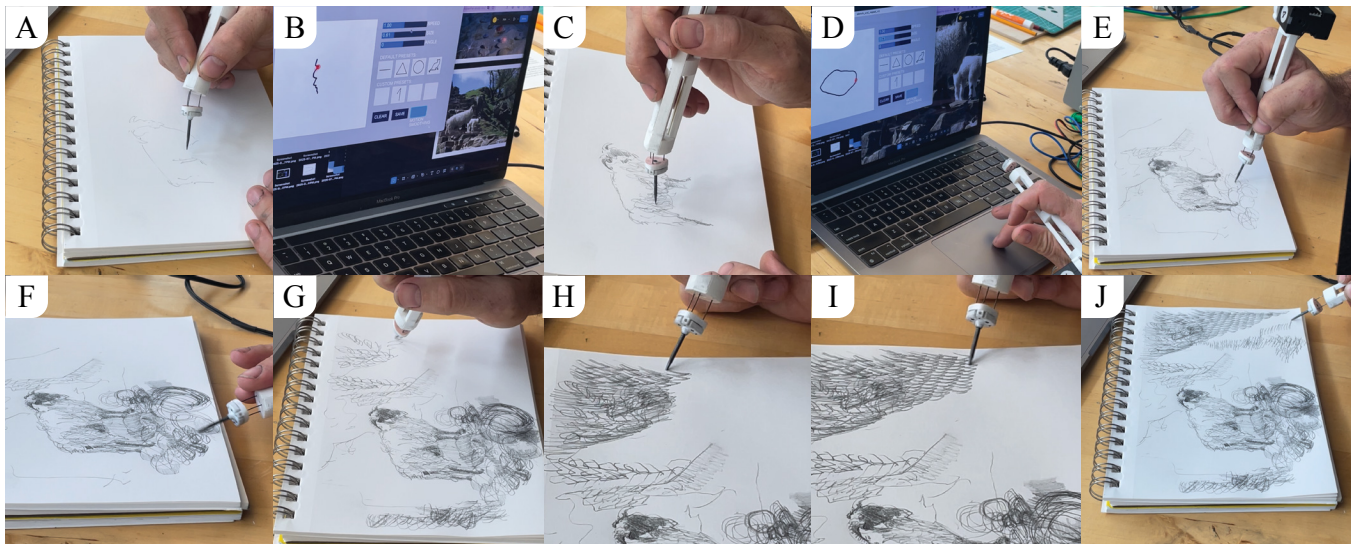


Figure 8: Sequential stages of the complete drawing process for P8's open-ended drawing task, described in detail in Section 5.3.

penPal to create marks while they translated and rotated the tip across the sheep to create the texture of its wool and add value (Fig. 8C), which they described as a “repetitive, shapely fill.”

After realizing they had neglected the rest of the drawing, they started making fast composition-level strokes with their hand while the tip continued the same fleece-like motion. Surprised by how the relatively slow speed of the tip allowed them to intuitively time their own motions, they said, “Being able to do that [draw a precise border to the right of the sheep], I couldn't tell you how I'm anticipating being able to make those two angles, but it felt very doable.” Continuing with the same tip motion, but slowing down their hand, P8 said that the longer graphite made them feel more confident in their decisions because it amplified *penPal*'s movement.

Stopping *penPal*'s tip again to add darker tones to the sheep, P8 recollected an earlier statement about using digital embroidery machines, which can only make one type of stitch, to do “foundational work” before switching to slower, more exploratory hand stitches. They drew a parallel to their use of *penPal* to fill in areas before stopping it for detail work.

Quickly breaking with this suggestion, P8 drew a boulder shape in the GUI (Fig. 8D) and started drawing stones under the sheep (Fig. 8E). When reminded that this was similar to the shape they highlighted in the van Gogh drawing as one they thought *penPal* could make, they decreased the motion size to match that of van Gogh's marks. This reminded them again of their hand-drawn warm-up textures, and they played with the size slider to add more variation. The mental connection to hand-drawing also prompted them to vary the weight of their marks, and P8 began to rhythmically apply force to *penPal* to create darker edges on one side of the boulders. P8 continued to apply this technique as they cycled through other tip motions, also adjusting the angle of the tool from perpendicular to the page to about 30°.

Switching to the **line** preset and lowering their angle to 10° (Fig. 8F), P8 started doing the kind of shading that they had previously stopped *penPal*'s motion to achieve. They said, “I think if I

had a MIDI interface with accelerometers or knobs, I would start to feel like I could make size and speed choices more intuitively.” They felt that to some degree, the flexibility they were developing with *penPal* was hindered by needing to switch their focus to the screen and guessing about the relationship between a slider's position and the motion that they wanted.

Using a fast **triangle** tip motion, P8 quickly drew tree forms (Fig. 8G), taking only 20 seconds to sketch in that quadrant of the page. This use of *penPal* was similar to the results generated by *Vignette*'s “example stroke” (tip motion) to “gesture” (hand motion) workflow, except here the example stroke and gesture were synchronous and interdependent [43]. Lifting and lowering *penPal* with the **triangle** preset had drawn individual stones, but translating it quickly with the same motion created plants.

P8 said that their initial frustration caused by the discrepancy between the path on screen and the strokes made by *penPal* (see Section 5.1) had given way to a curiosity about what kinds of marks it could make. They noticed that adjusting the angle of the tool could make the graphite “leap” off the page, drawing a “V” instead of a triangle (see Fig. 8H). This reminded them of van Gogh's drawing, and when they stopped moving their hand around and started scanning steadily to create rows of V's, they said that the resulting pattern, seen in Figure 8I, was the most fun they had had so far. This pattern, which reminded them of a knit texture, led them to make a connection to drawings that Ruth Asawa made with a stamp in the 1940's [5]. Reflecting on *penPal* and Asawa, P8 said, “It's being able to take something that is just like a mark, an interesting mark, and then by repetition and movement, I can make it feel like I'm looking at something else.” This stands in stark contrast to their earlier feelings about *penPal*'s limited range. While saying this, P8 adjusted how they were holding *penPal* and, using the very same **triangle**, drew the wobbly lines in Figure 8J.

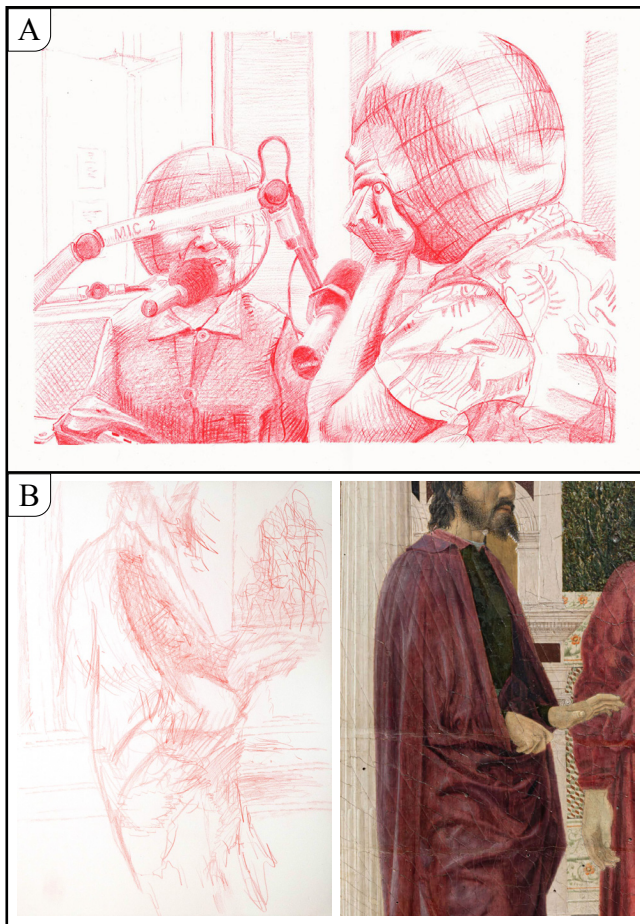


Figure 9: A) *Duet* (2020) [59], a drawing typical of David Muenzer’s art practice. B) (Left) A study from a section of Piero della Francesca’s *The Flagellation of Christ* (c. 1460) [19] that Muenzer drew in red pencil using *penPal*. (Right) A detail from the original painting.

5.4 Reflections from the Professional Demo

With *penPal*, we were interested in supporting idiosyncratic art practices. We believe a fuller understanding of the affordances of our system will require longer-term user deployments. To gain an initial impression of how a professional artist might engage with our system, we commissioned David Muenzer⁴ to spend two hours using *penPal* and one hour in a semi-structured interview. Muenzer makes a living by creating and exhibiting his own body of unique artwork and considers drawing a central practice. He was paid a \$200 (USD) honorarium and retains ownership over the physical copies of the drawings he made. In his normal studio practice, Muenzer uses red woodless colored pencils [48] to make drawings of humanoid figures in a variety of social situations (see Fig. 9A). These drawings, which often use photographs as reference images, rely heavily on hatching and shading techniques and exhibit fine

⁴<https://davidmuenzer.net/>

gradations in texture. At his request, we made a special tip for *penPal* using his preferred red pencils.

After being given the same introduction as the study participants and familiarizing himself with the interface, he completed two drawings with the system. Both drawings, one of which is shown in Figure 9 (Left), were studies made from digital images of painting by the Italian Renaissance painter, Piero della Francesca. He described using a consistent method for both, mostly holding *penPal* perpendicular to the paper and letting the tip make discrete hatching marks while he moved his hand or the paper underneath it. While he initially thought of this in terms of automating a process that aggravates his carpal tunnel syndrome, he was surprised at the way the speed of his hand was recorded in the varying spacing of *penPal*’s lines due to the contrast between the tip’s steady rhythm and his own acceleration. This led him to pay closer attention to the marks being made, noticing that “this is a gradient that you wouldn’t get from the arc that your wrist makes with a drawing tool.” Because the scale (the radius of the arc) of *penPal*’s hatch marks differs from his own, Muenzer thought that close observers would perceive that a special tool had been used to make the drawing.

Continuing on the theme of tools affecting the form of art, Muenzer stated that “Drawing is always in relationship to technology. Like, Piero’s perspective in *The Flagellation* probably looked like a kind of incredible naturalism in its moment, the depth and the ability to step past and around figures, and now it looks particularly wooden... maybe stage-like.” He was not sure what kind of relationship to technology *penPal*’s marks would communicate, but he appreciated that even though the system introduced an additional apparatus to the drawing process, no special equipment would be required to display the drawings made with it, in contrast to other new media technologies that artists have experimented with such as holograms and even VHS tapes.

Most significantly for the professional artist, *penPal* “shared enough with how I draw to become exciting or feel generative.” Muenzer contrasted this by speculating about attaching a paintbrush to his car and driving it around to make a drawing, saying, “That’s different, that’s novel, but [unlike *penPal*] it doesn’t have enough connection with my manual skills to sustain interest.”

6 Discussion

In this section, we discuss *penPal* as a tool that can fluidly transition between extensional and co-creational modes, which can support creative exploration through selective defamiliarization, and which, through its handheld form, natively supports tacit scale transitions.

6.1 Tool: Extension, or Collaborator?

In describing the working relationship between humans and computational tools, Human-Computer and Human-Robot Interaction researchers discuss paradigms like negotiation [20], mixed initiative [49], and communication [61] that assume a fundamental frame of the human and the system as *separate entities*. In hardware research, this is exemplified by works like *Machines as Co-Designers...*, which calls for rethinking digital fabrication machines as “live collaborators to aid in-situ creativity” by introducing new opportunities for negotiation [46] and *Wise Chisel...*, which outlines the

category of “smart handheld tools:” devices that collaborate in manual creation without hindering the tool’s “default function [91].”

Throughout our study, however, participants compared *penPal* to tools like pencils that have the capacity to feel “almost like a direct extension of my body [P2],” in addition to describing it as a collaborator. These two characterizations seem to point in opposite directions: on the one hand, a tool can feel like a separate agent engaged in interaction, and on the other, the boundary between tool and self is blurred or vanishes. This tension suggests an interesting middle ground between incorporating a tool and ascribing it agency that we feel stems from *penPal*’s qualities of being handheld, actuated, and allowing for access to existing skills.

P8, an experienced artist, explained that while *penPal* did not yet feel like a “prosthesis” in the way that pencils do, they were slowly developing the same kind of intimate relationship. This was apparent in their drawing process described above (Section 5.3), where they shifted from initially viewing *penPal* as a machine that could automate boring and repetitive tasks to something whose motion could combine with their own in novel ways that felt immediate and intuitive. On the other hand, P4, who stated that drawing requires him to consciously think about how to use his hand to translate his vision onto paper, looked for utilitarian ways that *penPal* could support him. In his final drawing (see Fig. 7C: P4), he “modularized” elements of the landscape by reusing the same motion paths for similar shapes while adjust their size and angle parameters in the GUI with his left hand. This suggests that *extensional* relations to actuated handheld tools depend either on the ability to access prior experience or to develop deep experience with the tool itself.

Perceiving *penPal* quite clearly as a collaborator, P3 said that “...here you feel that [*penPal*] is really participating in the drawing in its own way. And the way that it’s participating—and it comes from *its control*—is totally separated from the way that I’m behaving with the pen [emphasis added].” The fact that *penPal* moved simultaneously with her led P3 to feel like they were collaborating. This was not diminished by the control she had over the tip motion, but stemmed from the perceived unpredictability of motion paths like the *cat*. In her words, motions like this inscribed the “memory” of *penPal* in the outlines of a cone (see Fig. 7B: P3).

While our sample size is small, we noticed that experienced artists were more likely to describe *penPal* as *collaboratory*. Because collaboration involves giving up some measure of control over outcomes, we suspect that their experience helped them feel that less was at stake with steering their drawing towards a predetermined goal. This is supported by P2’s reflection on her overall experience, when she said, “I think [over time] I became a lot less interested in trying to copy things. And if anything, I had the feeling of not wanting to interrupt [*penPal*]. So I think it was an interesting interplay between like, “What do you want? How can I make you do what I think you want” Almost like the pen is an agent too.” In the next section, we discuss another way that relaxing control was involved in the creative process.

6.2 Creative Exploration through Selective Defamiliarization

As stated above, we observed that more experienced participants seemed readier to “let go” of the idea of fully controlling their

drawing results than novices. This allowed them to engage with *penPal* in a more dynamic way: when they wanted to exert control, they used similar strategies to novices (see Section 5.2.1), but when they wanted to explore unknown creative territory, they invented ways of “giving over” control to the device. P3’s “Ouija” grip is one example of this, as is the way she used the *cat* motion preset not for its semantic content, but for the complexity and unpredictability of its motion. In addition to situating *penPal* as a collaborator, these two actions can be understood in terms of *defamiliarization*, a tactic that artists employ as both a stylistic choice and as a method to help them generate ideas. We see the generative use of this in art school exercises that recommend students try drawing with their eyes closed [65] or with their non-dominant hand [76].

HCI has engaged with defamiliarization as a literary device enacted on the audience [6] as well as in this sense as a tool for helping artists break out of their familiar habits: citing group improvisational dance practices, Carlson, et al. create a framework for thinking about computational tools that support defamiliarization for choreography [14]—an apt connection given that at one point P8 described their experience with *penPal* as “dancing with the pen.” While Carlson, et al., map out four different paradigms of defamiliarization tools, each project is firmly located in a single quadrant. With *penPal*, we observed participants dynamically exploring a user-guided **selective defamiliarization**.

This is in contrast with the defamiliarizing effect of Lee and Ju’s adversarial robotic drawing pad, which operates independently from the artist to foil their plans [50]. By adjusting the ratios of how much they were contributing to the size and speed of *penPal*’s motion versus how much was coming from the motors and by changing their grips, some participants were able to draw in a way that was unexpected, yet pleasurable. Echoing P2’s comments about collaborating with *penPal*, but framing things in terms of what the experience meant for their own exploration, P8 said, “When I stopped being concerned with what the drawing would turn into like in terms of planning, it felt much more dancier because I was enjoying responding to what happens if I twist or lift up.” The design of *penPal*, where the actuated tool and the user have overlapping control over actions at the mark and texture levels, allows for these back-and-forth shifts between predictability and defamiliarization.

It is important to note that defamiliarization is not an experience that everyone enjoys. Towards the beginning of the study, P10, a novice drawer, described the feeling of *penPal* in her hand as “strange and disconnected” and the marks that she made with it as “foreign.” While this may represent an edge case, it suggests that selective defamiliarization might require careful scaffolding for some users as well as clear signposts for how to reclaim control.

6.3 Navigating Level Transitions

Reflecting on the drawing described in Section 5.3, P8 explained how their discoveries with *penPal* encouraged them to work outside of their usual process for making representational drawings:

“When I do draw based off of observation, I’m thinking about laying out composition, setting in value, coming in with tighter details, things like that. But with this, it was more about, like, the drawing is emerging because the mark-making is happening. And I find

that, I've always found that really fun, but it's particularly enjoyable because it's just sort of like... it's not effortless, but it's surprising."

This process, rooted in their classical academic training, proceeds hierarchically from the composition level down through texture-level value to mark-level details. As the drawing progresses, its resolution increases uniformly. With *penPal*, however, they felt like the tool natively operated at the "middle level" of textural mark-making, which encouraged a process where the overall composition emerged in a surprising and nonlinear way.

This was facilitated by their ability to quickly transition *penPal* from mark-level texture up to composition-level strokes or down to mark-level detail. From the period represented in Figure 8B until they began drawing stones in Figure 8D, they used the same tip motion to: 1) work at the texture level by slowly moving their hand to aggregate marks on the sheep's body, 2) add lower-level character to composition-level marks by rapidly moving their hand, timing their motion to take advantage of the motion of the tip, and 3) to add texture-level shading to the newly established compositional areas. Similarly, while they initially used their "boulder" motion path (Fig. 8D) to create stones that we consider mark-level because each one represents an individual stone rather than a stony texture, they adjusted the motion's scale up and started scanning their hand across the page to make just such a texture (Fig. 8F). Towards the end of their session, they quickly filled in the right side of the drawing (Figures 8D - J) exclusively using textures in the clearest demonstration of composition-level areas emerging from this middle-level activity.

While not every participant transitioned as fluidly or as many times between levels as P8, *penPal*'s support of work at both the mark and texture levels created other interesting opportunities. As discussed in Section 6.1, P4 felt that *penPal* allowed him to "modularize" mark-level actions, which are usually the focus of his drawing process, helping him shift his attention to composition-level decisions. P6 echoed this, saying, "It almost feels relaxing to just not have to think about making every single squiggle." P1, whose typical digital drawing practice proceeds from the highest level down through mark-level details like P8 described, said that he has been trying to break out of this habit. In this case, *penPal*'s ability to selectively defamiliarize the experience of drawing allowed him to fulfill this goal anchoring drawing at the texture level.

7 Future work

The *penPal* system is a functional, lightweight, modular robotic drawing tool, which allowed us to study texture-scale drawing practices with a handheld computational tool. The system itself could be improved to bring its form factor closer to that of a non-augmented drawing tool: it might be miniaturized with smaller motors and/or made fully wireless by integrating onboard battery power. These improvements would align with user comments about how the concentration of weight at the top of the tool caused them to hold *penPal* more vertically than they preferred. Additionally, while our users were all adults who we carefully instructed in the safe use of *penPal*, we observe that *penPal*'s unenclosed actuator design could pose safety risks; future work could add safety features such as a rubber boot or torque limits during retraction. Most

importantly, optimizing the design for robustness and simple repairs would help with longer term in-the-wild deployments.

Our GUI and its underlying heuristic motion-planning implementation allowed users to input basic shapes and lightly parameterize them. These might be broadened to include a wider range of path input modalities and/or further optimized path-planning (potentially including reinforcement learning and closed-loop control over tip position to account for hardware inaccuracies). The input system could itself be a fruitful avenue of design inquiry, following in the path of HCI research on playful inputs to fabrication systems [77]. Future work with the *penPal* system might also integrate more robust sensing, such as positional tracking, to extend *penPal*'s own scope of control to a larger physical scale.

8 Conclusion

This work presents *penPal*, a new actuated handheld drawing tool that supports dynamic mark-making by allowing users to rapidly and flexibly work at the levels of mark and texture. In this paper, we detailed the aspects of artistic drawing practices that informed our design and engaged with prior HCI research in drawing, texture, and augmented handheld tools. We shared findings from our 10-participant user study that communicate the strategies people used to negotiate control with this tool in order to work at different levels, to selectively defamiliarize their process as a creative exercise, and to shift between experiencing *penPal* as an extension of their body and as a collaborator. Finally, we engaged in a conversation with a professional artist who used our system, discussing his reflections on the relationship between art and art-making technologies. While drawing and handheld tools have long been focuses of research in HCI, we believe that there is still much to learn from the practices of studio artists and how they use their tools. With *penPal*, we suggest that texture provides a literal and metaphorical way of thinking about how artists shift between levels of activity and that supporting activity at the texture level provides opportunities for engaging with tools in novel ways.

Acknowledgments

We would like to sincerely thank our reviewers for their deep and thoughtful engagement with this paper. Their feedback was exemplary of the kind of intellectual community one hopes to encounter during the peer review process. We would also like to thank our colleagues and visitors who played with *penPal* at various points, offering both feedback and encouragement, including the members of AxLab and the People and Technology Seminar. We additionally thank Cella Sum for proofreading our manuscript and David Muenzer for allowing us to include reproductions of his drawings.

References

- [1] Adobe. 2025. <https://www.adobe.com/products/firefly/features/text-to-image.html>
- [2] Adobe. 2025. Illustrator. <https://www.adobe.com/products/illustrator.html>
- [3] Adobe. 2025. Photoshop. <https://www.adobe.com/products/photoshop.html>
- [4] Lea Albaugh, Scott E Hudson, and Lining Yao. 2023. Physically Situated Tools for Exploring a Grain Space in Computational Machine Knitting. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) (CHI '23). Association for Computing Machinery, New York, NY, USA, Article 736, 14 pages. <https://doi.org/10.1145/3544548.3581434>
- [5] Ruth Asawa. c.1948 - 1949. Untitled (BMC.117, BMC Laundry Stamp on Newsprint). <https://ruthasawa.com/art/black-mountain-work/#bwg8/62>

- [6] Genevieve Bell, Mark Blythe, and Phoebe Sengers. 2005. Making by making strange: Defamiliarization and the design of domestic technologies. *ACM Trans. Comput.-Hum. Interact.* 12, 2 (June 2005), 149–173. <https://doi.org/10.1145/1067860.1067862>
- [7] Claudia Betti and Teel Sale. 1980. *Drawing: A Contemporary Approach*. Holt, Rinehart and Winston, New York, NY, USA.
- [8] James F. Blinn. 1978. Simulation of wrinkled surfaces. In *Proceedings of the 5th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '78)*. Association for Computing Machinery, New York, NY, USA, 286–292. <https://doi.org/10.1145/800248.507101>
- [9] Samuelle Bourgault, Alejandro Aponte, Megumi Ondo, Emilie Yu, and Jennifer Jacobs. 2025. WORM: Programming Collaborative Robots Through Manual Actions for Craft-Aligned Digital Fabrication. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST) (Busan, South Korea) (UIST '25)*. Association for Computing Machinery, New York, NY, USA, 19 pages. <https://doi.org/10.1145/3746059.3747616>
- [10] Sam Bourgault and Jennifer Jacobs. 2024. Millipath: Bridging Materialist Theory and System Development for Surface Texture Fabrication. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference (Copenhagen, Denmark) (DIS '24)*. Association for Computing Machinery, New York, NY, USA, 50–68. <https://doi.org/10.1145/3643834.3661599>
- [11] Virginia Braun and Victoria Clarke. 2023. Toward good practice in thematic analysis: Avoiding common problems and be(com)ing a knowing researcher. *International Journal of Transgender Health* 24 (2023), 1–6. <https://doi.org/10.1080/26895269.2022.2129597>
- [12] Caroline E. Bryson and D. Caleb Rucker. 2014. Toward parallel continuum manipulators. In *2014 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, New York City, NY, USA, 778–785. <https://doi.org/10.1109/ICRA.2014.6906943>
- [13] Canva. 2025. <https://www.canva.com/ai-image-generator/>
- [14] Kristin Carlson, Sarah Fdili Alaoui, Greg Corness, and Thecla Schiphorst. 2019. Shifting Spaces: Using Defamiliarization to Design Choreographic Technologies That Support Co-Creation. In *Proceedings of the 6th International Conference on Movement and Computing (Tempe, AZ, USA) (MOCO '19)*. Association for Computing Machinery, New York, NY, USA, Article 17, 8 pages. <https://doi.org/10.1145/3347122.3347140>
- [15] Edwin Earl Catmull. 1974. *A subdivision algorithm for computer display of curved surfaces*. The University of Utah, Salt Lake City, Utah, USA. <https://doi.org/10.1145/280811.280920>
- [16] Bernard Chaet. 1979. *An Artist's Notebook: Techniques and Materials*. Holt, Rinehart and Winston, New York, NY, USA.
- [17] Bernard Chaet. 1983. *The Art of Drawing*. Wadsworth Group/Thomson Learning, Belmont, CA, USA. https://archive.org/details/artofdrawing0000chae_s2m8
- [18] Cuttlelola. 2015. Dotspen. <http://www.cuttlelola.com/>
- [19] Piero della Francesca. 1459 - 1460. The Flagellation of Christ. https://commons.wikimedia.org/wiki/Category:The_Flagellation_by_Piero_della_Francesca This painting, whose image is in the public domain, is in the collection of the Galleria Nazionale delle Marche, Italy.
- [20] 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 (Seoul, Republic of Korea) (CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2477–2486. <https://doi.org/10.1145/2702123.2702547>
- [21] Judith E. Fan, Wilma A. Bainbridge, Rebecca Chamberlain, and Jeffrey D. Wammes. 2023. Drawing as a versatile cognitive tool. *Nat Rev Psychol* 2 (2023), 556–568. <https://doi.org/10.1038/s44159-023-00212-w>
- [22] Cathy Mengying Fang, Lingdong Huang, Quincy Kuang, Zach Lieberman, Pattie Maes, and Hiroshi Ishii. 2024. An Accessible, Three-Axis Plotter for Enhancing Calligraphy Learning through Generated Motion. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (2024-05-11) (CHI '24)*. Association for Computing Machinery, New York, NY, USA, 1–11. <https://doi.org/10.1145/3613904.3642792>
- [23] Faraz Faruqi, Amira Abdel-Rahman, Leandra Tejedor, Martin Nisser, Jiaji Li, Vrushank Phadnis, Varun Jampani, Neil Gershenfeld, Megan Hofmann, and Stefanie Mueller. 2025. MechStyle: Augmenting Generative AI with Mechanical Simulation to Create Stylized and Structurally Viable 3D Models. In *Proceedings of the ACM Symposium on Computational Fabrication (2025) (SCF '25)*. Association for Computing Machinery, New York, NY, USA, Article 24, 15 pages. <https://doi.org/10.1145/3745778.3766655>
- [24] Faraz Faruqi, Maxine Perroni-Scharf, Jaskaran Singh Walia, Yunyi Zhu, Shuyue Feng, Donald Degraen, and Stefanie Mueller. 2025. TactStyle: Generating Tactile Textures with Generative AI for Digital Fabrication. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (2025) (CHI '25)*. Association for Computing Machinery, New York, NY, USA, Article 443, 16 pages. <https://doi.org/10.1145/3706598.3713740>
- [25] Frik H Fosssdal, Vinh Nguyen, Rogardt Heldal, Corie L. Cobb, and Nadya Peek. 2023. Vespidae: A Programming Framework for Developing Digital Fabrication Workflows. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference (Pittsburgh, PA, USA) (DIS '23)*. Association for Computing Machinery, New York, NY, USA, 2034–2049. <https://doi.org/10.1145/3563657.3596106>
- [26] 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, HI, USA) (CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 352, 16 pages. <https://doi.org/10.1145/3613904.3642622>
- [27] Devon Frost, Raina Lee, Eun-Ha Paek, 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 (CHI '24)*. Association for Computing Machinery, New York, NY, USA, 16 pages. <https://doi.org/10.1145/3613904.3642684>
- [28] GIMP. 2025. <https://www.gimp.org/>
- [29] Cédric Girerd and Tania K. Morimoto. 2021. Design and Control of a Hand-Held Concentric Tube Robot for Minimally Invasive Surgery. *IEEE Transactions on Robotics* 37, 4 (2021), 1022–1038. doi:10.1109/TRO.2020.3043668
- [30] Google. 2025. <https://gemini.google/overview/image-generation/>
- [31] Hasbro. 1950. OUIJA. https://tsdr.uspto.gov/#caseNumber=71546217&caseType=SERIAL_NO&searchType=statusSearch Trademark Serial No. 71546217, Filed 1948, Registered 1950.
- [32] Shiqing He and Eytan Adar. 2020. Plotting with Thread: Fabricating Delicate Punch Needle Embroidery with X-Y Plotters. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference (DIS '20)*. Association for Computing Machinery, Eindhoven, Netherlands, 1047–1057. <https://doi.org/10.1145/3357236.3395540>
- [33] Christopher S. Henshilwood, Francesco d'Errico, Karen L. van Niekerk, Laure Dayet, Alain Queffelec, and Luca Pollarolo. 2018. An abstract drawing from the 73,000-year-old levels at Blombos Cave, South Africa. *Nature* 562, 7725 (Oct. 2018), 115–118. <https://doi.org/10.1038/s41586-018-0514-3>
- [34] Richard Houston. 2026. Rembrandt and Mark Making. <https://www.nortonsimon.org/learn/schools-teachers/the-elements-of-art-a-drawing-guide/rembrandt-and-mark-making>
- [35] Ashley Hurst. 2019. How to Draw Texture. <https://thevirtualinstructor.com/blog/how-to-draw-texture>
- [36] Takeo Igarashi. 2025. Easy and Fast? Rethinking the Future of Content Creation Tools. https://www-ui.is.s.u-tokyo.ac.jp/~takeo/papers/UIST2025_vision_slide.pdf
- [37] Inlumino Heart Ink. 2024. Electric Pro Dot Pen. <https://inluminoheart.com/product/electric-dot-pen>
- [38] Inkscape. 2025. Inkscape. <https://inkscape.org/>
- [39] Jennifer Jacobs, Joel Brandt, Radomir Mech, and Mitchel Resnick. 2018. Extending Manual Drawing Practices with Artist-Centric Programming Tools. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. <https://doi.org/10.1145/3173574.3174164>
- [40] Jennifer Jacobs, Sumit Gogia, Radomir Mech, and Joel R. Brandt. 2017. Supporting Expressive Procedural Art Creation through Direct Manipulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, Denver Colorado USA, 6330–6341. <https://dl.acm.org/doi/10.1145/3025453.3025927>
- [41] Gabe Johnson, Mark D. Gross, Jason Hong, and Ellen Yi-Luen Do. 2009. Computational Support for Sketching in Design: A Review. *Found. Trends Hum.-Comput. Interact.* 2, 1 (Jan. 2009), 1–93. <https://dl.acm.org/doi/10.1561/1100000013>
- [42] Heidi Kay. 2012. OT Product of the Week: Squiggle, Wiggle Writer: Fun Therapy Tool! <https://www.pediastaff.com/blog/ot/ot-product-of-the-week-squiggle-wiggle-writer-fun-therapy-tool-9621>
- [43] Rubaiat Habib Kazi, Takeo Igarashi, Shengdong Zhao, Richard C. Davis, and Kenshi Takayama. 2012. Vignette: a style preserving sketching tool for pen-and-ink illustration with texture synthesis. In *ACM SIGGRAPH 2012 Posters (Los Angeles, California) (SIGGRAPH '12)*. Association for Computing Machinery, New York, NY, USA, Article 29, 1 pages. <https://doi.org/10.1145/2342896.2342934>
- [44] Soheil Kianzad, Yuxiang Huang, Robert Xiao, and Karon E. MacLean. 2020. Phasking on Paper: Accessing a Continuum of PHysically Assisted SKetchING. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (Honolulu, HI, USA) (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. <https://doi.org/10.1145/3313831.3376134>
- [45] Hyunjung Kim, Seoktae Kim, Boram Lee, Jinhee Pak, Minjung Sohn, Geehyuk Lee, and Woojun Lee. 2008. Digital rubbing: playful and intuitive interaction technique for transferring a graphic image onto paper with pen-based computing. In *CHI '08 Extended Abstracts on Human Factors in Computing Systems (CHI EA '08)*. Association for Computing Machinery, New York, NY, USA, 2337–2342. <https://doi.org/10.1145/1358628.1358680>
- [46] Jeeun Kim, Haruki Takahashi, Homei Miyashita, Michelle Annett, and Tom Yeh. 2017. Machines as Co-Designers: A Fiction on the Future of Human-Fabrication Machine Interaction. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems (Denver, Colorado, USA) (CHI EA '17)*. Association for Computing Machinery, New York, NY, USA, 790–805. <https://doi.org/10.1145/3027063.3052763>

- [47] Kelsey Kloss. 2018. That Magical Moment Your Preschooler Starts Coloring Inside the Lines. <https://www.scholastic.com/parents/books-and-reading/raise-a-reader-blog/developmental-milestones-coloring-in-the-lines.html>
- [48] Koh-I-Noor. 2025. Progresso. <https://www.kohinoorusa.com/woodlesscolor>
- [49] Tomas Lawton, Francisco J Ibarrola, Dan Ventura, and Kazjon Grace. 2023. Drawing with Reframer: Emergence and Control in Co-Creative AI. In *Proceedings of the 28th International Conference on Intelligent User Interfaces (IUI '23)*. Association for Computing Machinery, New York, NY, USA, 264–277. <https://doi.org/10.1145/3581641.3584095>
- [50] Shayla Lee and Wendy Ju. 2024. Adversarial Robots as Creative Collaborators. In *Companion of the 2024 ACM/IEEE International Conference on Human-Robot Interaction (HRI '24)*. Association for Computing Machinery, New York, NY, USA, 655–658. <https://doi.org/10.1145/3610978.3640560>
- [51] Golan Levin. 1998. Yellowtail. <https://www.flong.com/archive/projects/yellowtail/index.html>
- [52] Yu-Chen Lin, Chieh-Hsiang Hsu, Cheng-Feng Lin, Hsiu-Yun Hsu, Jin-Wei Liu, Chien-Hsien Yeh, and Li-Chieh Kuo. 2022. Pen-grip kinetics in children with and without handwriting difficulties. *PLOS ONE* 17, 6 (06 2022), 1–15. <https://doi.org/10.1371/journal.pone.0270466>
- [53] Robert A. MacLachlan, Brian C. Becker, Jaime Cuevas Tabares, Gregg W. Podnar, Louis A. Lobes, and Cameron N. Riviere. 2012. Micron: An Actively Stabilized Handheld Tool for Microsurgery. *IEEE Transactions on Robotics* 28, 1 (2012), 195–212. <https://doi.org/10.1109/TRO.2011.2169634>
- [54] Moshe Mahler, Yuchen Liu, and Jodi Forlizzi. 2025. *The Evolution of Artists' Toolsets: A Call for Artist-Driven Design*. Association for Computing Machinery, New York, NY, USA, 335–339. <https://doi.org/10.1145/3715668.3736335>
- [55] Blick Art Materials. 2025. Sennelier Red Ochre Soft Pastel. <https://www.dickblick.com/items/sennelier-soft-pastel-red-ochre-067/>
- [56] Hayley McClintock, Fatma Zeynep Temel, Neel Doshi, Je-sung Koh, and Robert J. Wood. 2018. The milliDelta: A high-bandwidth, high-precision, millimeter-scale Delta robot. *Science Robotics* 3, 14 (2018), eaar3018. <https://www.science.org/doi/abs/10.1126/scirobotics.aar3018>
- [57] Ian E Moyer, Samuelle Bourgault, Devon Frost, and Jennifer Jacobs. 2024. Throwing Out Conventions: Reimagining Craft-Centered CNC Tool Design through the Digital Pottery Wheel. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems (CHI '24)*. Association for Computing Machinery, New York, NY, USA, 22 pages. <https://doi.org/10.1145/3613904.3642361>
- [58] 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>
- [59] David Muenzer. 2020. Duet. <https://davidmuenzer.net/> Reproduced with the permission of the artist.
- [60] Ken Nakagaki and Yasuaki Kakehi. 2014. Comp*Pass: a compass-based drawing interface. In *CHI '14 Extended Abstracts on Human Factors in Computing Systems (CHI EA '14)*. Association for Computing Machinery, New York, NY, USA, 447–450. <https://doi.org/10.1145/2559206.2574766>
- [61] Clifford Nass, Jonathan Steuer, and Ellen R. Tauber. 1994. Computers are social actors. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (Boston, Massachusetts, USA) (CHI '94)*. Association for Computing Machinery, New York, NY, USA, 72–78. <https://doi.org/10.1145/191666.191703>
- [62] Nexmetal. 2025. <https://nexmetal.com/products/nitinol-superelastic-wire?variant=21956546628> Cost for 0.5 mm wire at time of writing was \$1.34 (USD) per foot.
- [63] David Nishimura. 2025. Pen Measurements. https://www.vintagepens.com/pen_measurements.shtml Of the 42 pens measured in this blog post, the minimum and maximum diameters are 8.4mm and 13.7mm, and the mean diameter is 11.6mm.
- [64] OpenAI. 2025. <https://chatgpt.com/>
- [65] D. Petrovich, R. White, and Paper Monument (Organization). 2012. *Draw it with Your Eyes Closed: The Art of the Art Assignment*. Paper Monument, Brooklyn, NY, USA. <https://books.google.com/books?id=JdNeLwEACAAJ>
- [66] 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, 14 pages. <https://doi.org/10.1145/3544548.3580691>
- [67] Sullivan Products. 2025. <https://sullivanproducts.com/products/s507-032-cable>
- [68] Alec Radford, Jong Wook Kim, Tao Xu, Greg Brockman, Christine McLeavey, and Ilya Sutskever. 2023. Robust speech recognition via large-scale weak supervision. In *Proceedings of the 40th International Conference on Machine Learning (Honolulu, Hawaii, USA) (ICML '23)*. JMLR.org, New York City, NY, USA, Article 1182, 27 pages. <https://proceedings.mlr.press/v202/radford23a/radford23a.pdf>
- [69] Robotis. 2025. DYNAMIXEL Shield for Arduino MKR. <https://www.robotis.us/dynamixel-shield-for-arduino-mkr-series/?srsltid=AfmBooPU-WX7E5ppcXPLbAXqJbuuTlwaH0pZuK0gWvHR68On6o8eozK> Unit cost of \$21.97 (USD) at time of writing..
- [70] Robotis. 2025. DYNAMIXEL XL330–M266–T. <https://www.robotis.us/dynamixel-xl330-m266-t/> Unit cost of \$27.49 (USD) at time of writing..
- [71] Olinde Rodrigues. 1840. Des lois géométriques qui régissent les déplacements d'un système solide dans l'espace, et de la variation des coordonnées provenant de ces déplacements considérées indépendamment des causes qui peuvent les produire. *Journal de mathématiques pures et appliquées* 5 (1840), 380–440. https://www.numdam.org/item/JMPA_1840_1_5__380_0/
- [72] Kimiko Ryokai, Stefan Marti, and Hiroshi Ishii. 2004. I/O Brush: Drawing with Everyday Objects as Ink. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York City, NY, USA, 303–310. <http://doi.org/10.1145/985692.985731>
- [73] Micah Scott. 2021. *Scanlime055 – Pen Wiggler*. Retrieved 2026-01-25 from <https://scanlime.org/2021/05/scanlime055-pen-wiggler/>
- [74] Ticha Sethapakdi and James McCann. 2019. Painting with CATS: Camera-Aided Texture Synthesis. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) (CHI '19). Association for Computing Machinery, New York, NY, USA, 1–9. <https://doi.org/10.1145/3290605.3300287>
- [75] M. P. Sheehy and C. D. Marsden. 1982. Writers' Cramp—A Focal Dystonia. *Brain* 105, 3 (09 1982), 461–480. <https://doi.org/10.1093/brain/105.3.461>
- [76] Peter Stanyer and Terry Rosenberg. 1999. *A Foundation Course in Drawing*. Watson-Guptill Publications, New York, NY, USA.
- [77] Blair Subbaraman and Nadya Peek. 2024. Playing the Print: MIDI-Based Fabrication Interfaces to Explore and Document Material Behavior. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '24)*. Association for Computing Machinery, New York, NY, USA, 8 pages. <https://doi.org/10.1145/3613905.3650966>
- [78] True Grit Brush Supply. 2025. <https://www.truegrittexturesupply.com/>
- [79] Virtuoso Surgical. 2023. Microsurgery Assistance Robot. <https://virtuososurgical.net/technology/>
- [80] Ivan E. Sutherland. 1963. Sketchpad: a man-machine graphical communication system. In *Proceedings of the May 21-23, 1963, Spring Joint Computer Conference* (Detroit, Michigan) (AFIPS '63 (Spring)). Association for Computing Machinery, New York, NY, USA, 329–346. <https://doi.org/10.1145/1461551.1461591>
- [81] The Unsharpen Team. 2022. How Long Is a Pencil? <https://unsharpen.com/how-long-is-a-pencil/> Of the 12 unsharpened pencils measured in this blog post, the minimum and maximum lengths are 175mm and 200mm, and the mean length is 183mm..
- [82] The Unsharpen Team. 2022. How Long Is An Average Pen? <https://unsharpen.com/how-long-is-a-pen/> Of the 11 uncapped pens measured in this blog post, the minimum and maximum lengths are 122mm and 148mm, and the mean length is 133.5mm..
- [83] The Unsharpen Team. 2022. How Wide Is a Pencil? <https://unsharpen.com/how-wide-is-a-pencil/> Of the 18 pencils measured in this blog post, the minimum and maximum diameters are 7.2mm and 9.8mm, and the mean diameter is 7.8mm..
- [84] Hart Toys. 1991. Squiggle Wiggle Writer. <http://harttoys.com/swwriter.html>
- [85] 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 City, NY, USA, 1–15. <https://doi.org/10.1145/3411764.3445653>
- [86] Hannah Twigg-Smith and Nadya Peek. 2023. Dynamic Toolchains: Software Infrastructure for Digital Fabrication Workflows. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco CA USA). ACM, New York City, NY, USA, 1–20. <https://dl.acm.org/doi/10.1145/3586183.3606802>
- [87] Vincent van Gogh. 1888. Street in Saintes-Maries-de-la-Mer. <https://www.metmuseum.org/art/collection/search/336318> In the collection of the Metropolitan Museum of Art, New York City, NY, USA.
- [88] Vincent van Gogh. 1888. View of Arles. <https://rismuseum.org/art-design/collection/view-arles-42212a> In the collection of the RISD Museum, Providence, RI, USA.
- [89] Junichi Yamaoka and Yasuaki Kakehi. 2013. dePEN: 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>
- [90] 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)*. Association for Computing Machinery, New York, NY, USA, 2613–2616. <https://doi.org/10.1145/2470654.2481361>
- [91] Amit Zoran, Roy Shilkrot, Pragnu Goyal, Pattie Maes, and Joseph A. Paradiso. 2014. The Wise Chisel: The Rise of the Smart Handheld Tool. *IEEE Pervasive Computing* 13, 3 (2014), 48–57. <https://doi.org/10.1109/MPRV.2014.59>
- [92] Amit Zoran, Roy Shilkrot, and Joseph Paradiso. 2013. Human-Computer Interaction for Hybrid Carving. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology (UIST '13)*. Association for Computing Machinery, New York City, New York, USA, 433–440. <https://doi.org/10.1145/2501988.2502023>