Craft in the age of robots

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Abstract
Through a series of robotically fabricated drawings, the work investigates the confluence of a creative analog medium like painting and the possibilities for custom production enabled by industrial automation. A six-axis tabletop robot is programmed to execute the toolpath of parametrically-designed linework using a 3D-printed actuator that holds a soft brush pen. Instead of working on a flat bidimensional target surface, the soft brush navigates the 2.5-D space dissolving the fully controlled digital inputs into unique ink marks. A bespoke Python script in Grasshopper is developed to optimize the digital-physical translation in which software variables push the brush on the paper incrementally in predetermined ways. As a result, the final appearance of the programmed paths remains uncertain due to ongoing negotiations between the digital procedural drawings and the robotic mark-making exploration in the physical space. Each drawing reflects an extent of craft practice as it represents the unique manifestation of non-repeatable digital and physical relationships in which two-dimensional marks on paper have three-dimensional implications. By adopting a digital fabrication tool traditionally rooted in delivering efficient repetitive tasks, it is possible to establish a culture of technology that empowers designers to deviate from the predictability of the outcomes and find space for debate.

Author keywords
Robotic mark-making; digital craft; robotic drawings; digital fabrication.

Introduction and scope of the work
The recent influx of digital manufacturing tools across various trades has set the stage for convergence between design and other industries. This opportunity to integrate creative professions with innovative implementation sequences allows makers, product designers, and architects to participate in a broader interdisciplinary context (Timberlake & Kieran, 2003). Similar file formats enable different possibilities in the realm of additive manufacturing, numerical control machining, and robotic execution of recursive tasks. However, in the design field, there is still a tendency to view technological development as an external factor, particularly in digital applications (Picon, 2022). To overcome this, designers should leverage the culture of technology to reframe their agency when working with adjacent disciplines.
The research featured in this paper is situated at the intersection of computational design, digital fabrication, automation, and craft, confronting an old form of analog expressions like painting and the opportunities for custom production afforded by industrial robotics.

Some argue that automated technologies can depersonalize the creation of objects, taking away the human element and transferring the necessary skills to machines (Boza, 2006). Rather, the project endeavors to investigate the concepts of technology and craft "getting the most out of the machines" (McCullough, 1996) by reorienting tools and processes through the bespoke materialization of digital media.

Painting is used as an application case since, traditionally, learning to paint has meant understanding how to hold the brush, test the pressure on the canvas, observe the resulting brush strokes, and build confidence in the dexterity of sequential gestures. The analog process relies on the maker's embodied skills to achieve consistent outcomes (Pye, 1968), and its success depends on their ability to craft the desired outcome. As a counterpoint, in this research context, a disembodied tool is used to extend the capabilities of human hands fostering a process of re-learning how to paint within a digital ecosystem using a retired automotive welding robot. The craft-oriented approach of the project aims at unbundle automation from the serial repetition of identical copies (Carpo, 2017) through the production of parametrically-designed linework drawings with a soft brush. The brush encompasses the 2.5-D space by retracting and pushing against the target sheet of paper, following a scripted set of rules. This procedure creates one-off ink marks that can only be loosely captured in the digital simulation. Drawing iterations are collected into a sketchbook (Figure 1), an everyday object deployed for annotations and hand sketches, as a learning device (Rowland & Howe, 2001) that

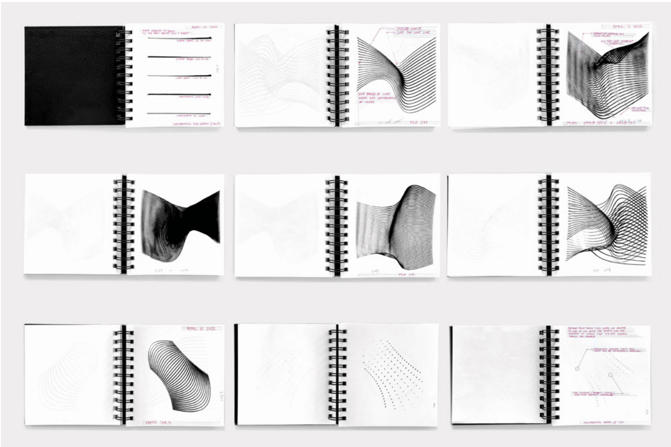

Figure 1. The sketchbook filled with robotic drawings and hand annotations describing the process.

conveys evidence of material iterations to discover unexpected insights into technique and materials (Sennett, 2008).

Elements of innovation: from machinery precision to craftwork

In the state-of-the-art of design representation, new disciplinary approaches are being explored in education and practice. One example is the use of robots or cartesian plotters for making digital drawings, which is becoming a common practice in technology-focused higher education institutions (Johnson & Vermillion, 2016). In the research field, Carl Lostritto has developed a custom Python-based workflow that effectively materializes the craft of hatching with computational lines using an automatic pen plotter (Lostritto, 2016). The Material Artifact Studio, led by Marcus Farr, also employs a similar tool for augmenting drawing processes (Farr, 2020). Rhett Russo has suggested the application of CNC tooling for transferring generative drawing information onto physical media such as textiles (Russo, 2010). Curime Batliner, in the exhibition *Drawing Codes*, displays a visual art project that uses an industrial robot to layer multiple line systems with ink on paper (California College of Art, 2017). Furthermore, a compelling point of view is offered by the multimedia artist Sougwen Chung, who works in conjunction with AI-enabled robotic arms trained to follow her drawing style and gestures to create collaborative outcomes (Chung, 2020).

The common thread of these experiments carries the qualities of materials, machine timing, data structure sequencing, and design accuracy, where the intricate complexity of the drawings challenges human abilities to produce comparable outcomes by hand. However, unlike the method discussed in this research, in these precedents every aspect of the line work is controlled with a predictable translation between concept and execution. Instead, the primary interest of the presented investigation lies in the uncertainty and unpredictability of each creative effort, giving digital data expressive capacity through materiality, with the potential to translate two-dimensional intelligent drawings into three-dimensional artifacts.

Methodology: robotic mark-making

The research process involves the definition of an experimental digital fabrication workflow consisting of the following routine: algorithms-aided digital modeling to develop the linework, geometry translation into a programming language, 6-axis robotic implementation of the exported toolpaths, procedural iterations, and evaluation of the outcomes.

Figure 2. The tooling setup with five tabletop ABB robots equipped with 3D-printed pen holders.

Five ABB tabletop robots are used to make the material drawings (Figure 2). Each robot is equipped with a simple actuator, a 3D-printed pen holder that keeps a soft brush in place perpendicular to the industrial arm's end, namely the sixth axis. A plywood board serves as a reference surface for the physical workspace and is leveled by taping clay underneath the four corners. The target drawing area is given by 96g square of paper in a 6″x6″ wire-bound sketchbook.

The design outcomes result from the mathematical re-sampling of data using Grasshopper, in which the generative rules are destructured into base elements of geometry and ultimately implemented with inkwork (Figure 3). Drawing types seek three-dimensional complexity inspired by phenomena in the physical world, such as those listed below.

Fillings

This method involves dividing two parallel spline curves into segments of equal length, then projecting points onto the outer side of the curves and parametrizing them by a polar rotation. The process generates a series of blended lines that can vary in density depending on the input values used.

Folds

The script is inspired by motion efficiency studies conducted by Frank and Lillian Gilbreth (Smithsonian Institution, n.d.). It creates line patterns that mimics the biomechanics of the arm, including straight segments, joints, and rotation nodes.

Fields

The software interprets the behavior of magnetic spin forces interacting in a particle field to compute field lines through points in space. It generates the drawing layout procedurally, starting from a set of vectors on a grid.

Flowlines

Looking at Durer's hatching techniques (Durer, 1973), the script simulates water flow on a double-curved topography using parametric controls. The topography is divided into a grid of points, and all the normal directions are extrapolated relative to the surface. The flow lines are calculated by comparing the normal vectors to the point projections along the z-axis. The steeper the topography gradient, the smaller the angle between the two vectors, and the shorter the flow line.

Before exporting an executable script, the three-dimensional parametrically-designed digital drawings are scaled within a bounding box described by the values (x, y, 0.25 mm). The x and y dimensions are the size of the destination paper template, while the fixed z value represents the maximum depth the physical brush will push onto it. This results in the soft brush navigating the 2.5D space, dissolving the precise digital inputs into unique ink marks. Every ink trace intelligently conveys meaning and multiple types of information, such as the subtle relationship between the digital 3D world and the physical 2D drawings. Since the digital lines do not lay on a flat surface, the robot's speed and directionality of each toolpath affect the lines' appearance. Dense linework can merge into blended ink patches, and overlapping lines enhance the readability of discernible surfaces without compromising the visual clarity of each individual layering sequence.

A bespoke Python-based Grasshopper plug-in is developed to optimize the translation from digital to physical. In addition to generating cartesian machine language code with accurate robotic joint configuration, the script detects the point or line closest to the top surface of the drawings' bounding box. This approach allows for calibrating the workspace and adjusting the robot's tool center point (TCP), which is the brush tip. The initial TCP, or calibration depth corresponding to the pen's length, is 178.75 mm. At each drawing attempt, the teach pendant, or robot controller, prompts the option to regulate the TCP accurately to the tenth of a millimeter. Progressively, the input number is reduced, responding to the wear of the pen tip and ink discharge. The tool settings, number of iterations, and file information are annotated in the sketchbook after each drawing. This methodical approach adds layers of knowledge about the process and deducts speculative findings from such observations. The final work demonstrates the development of new forms of drawing conveyed by an industrial robotic arm, where data and custom digital scripting are a means to pursue the materialization of craft through automation.

The research underwent two stages of optimization and review, using students' outcomes to validate project intentions and results. Between the summer and fall of 2022, the possibility of producing robot-informed parametric drawings was offered in the context of the DigitalFUTURES consortium (DigitalFUTURES, 2022), an international group in education with a focus on computational design and digital fabrication, and the Association for Computer Aided Design in Architecture (ACADIA, 2022). Both experiences were an opportunity to share the idea of amplifying the meaning of data by translating matter into computational artifacts with a wider audience. Such artifacts engage the organization of linework in a painterly manner, using mathematical functions to construct new material wholes.

Results and discussion

Leonardo Da Vinci argued that the act of painting enables the mental conversation, *il discorso mentale*, in which an image formed in one's mind helps reflect on the details to be included or excluded in the final drawing. He believed that focusing on those visual elements was more important than practicing the technique. According to Leonardo, artists do not learn to paint, but they paint to learn (Neumeier, 2012). A similar approach comes to mind while generating drawings using computation. The outcomes document the various attempts, repetitions, parameters, and circumstantial variables such as ink level, paper texture, and environmental humidity that play concurrently with the designers' whim. Different tools and software settings are used to achieve each robotic iteration, which reflects the programmed lines' length, density of target points on the generated toolpath, and pattern overlays. The nuances between sequential implementations are captured by repeatedly executing the same script on different pages (Figure 4). These observations can only be made by actively engaging in actual making (Figure 5).

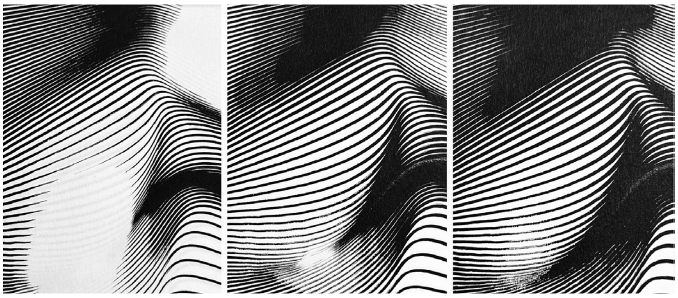

Figure 4. Drawings iterations obtained executing a script multiple times with different tool configurations.

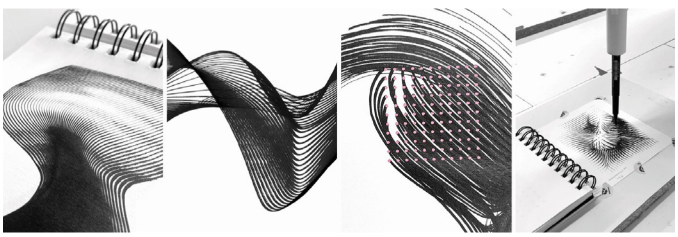

Figure 3. Sequence of linework-ink-based drawing types: Fillings, Folds, Fields, and Flowlines.

The recurring theme of the geometric line is inspired by Tim Ingold's philosophical description of these kinds of entities. Unlike concluded objects like blobs, lines are a metaphor for interaction with the external world. They do not resolve the continuity of things or build a unified whole from disparate parts. Instead, their role is to foster a principle of movement where intricate connections form alliances of the base matter (Ingold, 2015). The dimension of motion, connected to the machine's run-time, in fact, pervades the drawings.

A methodical exploration is pursued to share different reflections on the successes and failures of this type of work.

Figure 5. Long exposure photo depicting the robotic mark-making process.

Procedural artists like Sor Lewitt, Vera Molnar, Bridget Riley, and Darel Carey are used as references to help build discipline toward a critical and diligent use of technology. Sol Lewitt's instructional wall drawings highlight the ambiguity of lines as fundamentals of geometry that exist vividly as mental constructs and less so as elements of nature. Exemplary works are the *Wall Drawing 86* (1971), in which ten thousand lines cover a wall surface evenly as an upfront conveyance for his ideas, and the etching on paper *Straight and not Straight Lines* (2003) that portrays lines as unique and individual manifestations of the human touch. This approach uses seriality and repetition as drivers to conceptualize geometric rules and relationships into base components of human thought. Vera Molnar's drawings' variations depict a pioneering agenda toward generative design aesthetics. Her collection of plotter drawings conveys a kinematic orchestration of lines controlled by rigorous arbitrary ordering systems. Among others, it is worth mentioning *Segments Inclinés A* (1984) and *Interruptions* (1968-69), where the artist begins with a grid of straight lines of equal length, and applies random rotations to each line, resulting in a densely complex pattern. The pattern suggests the presence of various forces that disrupt a regular structure, introducing an element of chaos. Bridget Riley's optical illusions, such as the paintings *Current* (1964) and *Winged Curve* (1966), require the viewers to shift their gaze across the canvas to understand the portrayed play of emotions within the abstract linework and, therefore, encourage them to think of 2D lines as an opportunity to build 3D spatiality. The robotic mark-making work also reflects contemporary visual artist Darel Carey's procedure to manipulate the perception of wall surfaces, as displayed in the art piece *Topographical Space No.1* (2016). The application of black tape to create large-scale line patterns determines a uniquely crafted experience of the space, which delivers an illusion of apparent motion.

Using a soft brush pen to negotiate agency with a robotic arm allows for finding a breakpoint between the upstream simulation and the downstream implementation. The work doesn't seek the manifestation of tooling precision but instead emphasizes subtle differences between iterations, drawing nuances, and variability of results. Additionally, zooming into the drawings augments the layers of readability of the pieces and accentuates a perceptible ink texture (Figure 6). A closer look outlines the individual ink traces, independently from the cohesive image, and brings attention to the directionality of the toolpath that generated them.

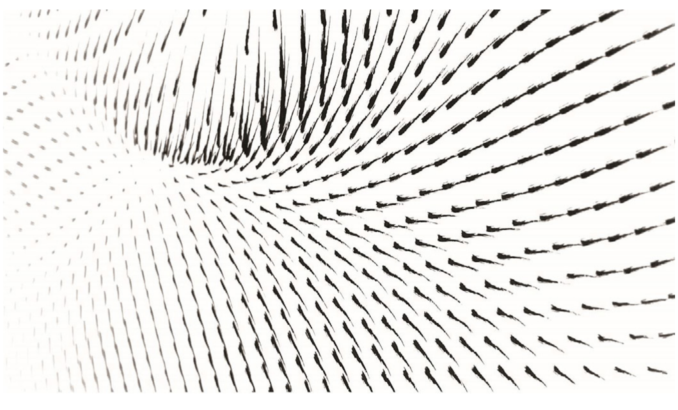

Figure 6. Zoomed in documentation into one of the robotically-implemented drawings using a soft brush.

The illustrated design tactics treat data, time, motion, actuators, and ink equally as materials.

Conclusions

In the robotic mark-making process, information gains expression through a custom workflow that merges computation and making in the presence of digital tools. Tension is discovered between the procedural aspect of the drawings and their visualization in the physical space that transcends technology itself. While the geometric control is manageable through input-output digital variables, the final appearance of the programmed paths remains uncertain. Through a planned loss of digital precision, each drawing is the unique manifestation of non-repeatable digital and physical relationships in which two-dimensional marks on a sheet of paper have three-dimensional implications.

While informed simulations offer a sense of determinacy, making physical iterations allows for exploring unknown domains and questioning established computational design rules. Recognizing their limitations and identifying gaps in their reach emphasizes material unpredictability. One intriguing realm of exploration for digital fabrication and intelligent making is understanding variations within the indeterminate regions of possibility, such as transitions, boundaries, and ink blends where points of shift occur. These conditions can be triggered by various factors, like circumstantial environmental forces, and reveal unexpected behaviors, leading to new knowledge.

Design customization involves fabrication tools, design variables, and material features. By adopting a precise fabrication technology, it is possible to diverge from the predictability of the outcomes and find space for debate. Robotics invites a sense of precision and control, but it also opens up new realms of exploration in the indeterminate areas given by temporal variability that interact with physical surfaces.

The potential to expand these processes to the third dimension and to the scale of larger components for interior design or architecture is a fascinating possibility that remains open for development. Ultimately, investigating the craft of robotically generated drawings represents an attempt to realign tools from other disciplines through the approach of designers in an advanced territory of making.

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Digital files and additional material

For supplementary information regarding video tutorials, Python coding, and Grasshopper definitions, please do not hesitate to contact the corresponding author.

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