Direct and Immediate Drawing with CNC Machines

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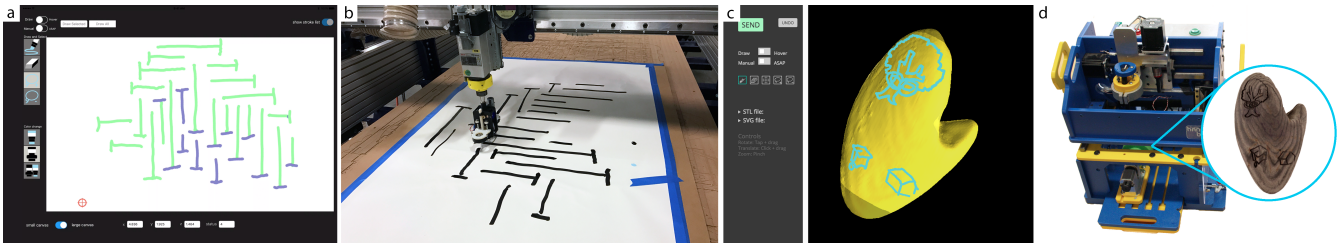

Figure 1: LINC's interface enables interactive CNC drawing and engraving. (a) The 2D design tool. (b) The modified large-scale CNC router that fabricates artworks. (c) The 3D design tool. (d) The engraved object mounted inside a desktop CNC router.

ABSTRACT

We investigate how the immediate control of computer numerical control (CNC) machines can narrow the design-fabrication gap and combine manual art practice with digital fabrication. LINC (Live Interactive Numeric Control) is a sketch-based digital design tool for authoring 2D or 3D artworks in near-real time. To use LINC, users draw strokes which are then executed in one of three modes—*static*, *manual*, or *as soon as possible*—by either a large-scale or desktop-sized modified CNC router. We evaluate LINC through a study with eight artists.

CCS CONCEPTS

•**Human-centered computing** → **Interface design prototyping;** *User interface toolkits;*

KEYWORDS

design tools, interactive fabrication, sketching

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1 INTRODUCTION

Conventional asynchronous digital fabrication workflows allow users to carefully iterate their designs before committing to a potentially time-consuming fabrication process. However, separating design from fabrication also creates some drawbacks: long temporal gaps prevent interactively working with and reacting to the material. On the other hand, a completely synchronous design and fabrication loop, as Willis et al. explore, while immediate, neither permits planning nor handles mistakes gracefully [Willis et al. 2011]. We therefore developed a hybrid asynchronous-interactive framework, designed around the conventions of manual drawing, to let artists actively manage this offline to real-time spectrum. By preserving the advantages of an asynchronous workflow but allowing for live, stroke-based control, we open a greater space for reflection-in-action [Winograd 1996]—reactions and actions to surprises and immediate material qualities during fabrication, which are important in art practice.

2 LINC: A FRAMEWORK FOR CNC DRAWING

Using a tablet, users digitally author objects in LINC, a stroke-based design tool (see Figure 1 a & c). To fabricate their designs, users transition between three execution modes over the course of creating their works: (1) *static*, which sends all strokes at once like in traditional fabrication; (2) *manual*, through explicit selection and confirmation; or (3) *as soon as possible (ASAP)*, with the machine "following" their mark-making either immediately or following a user-specified delay. Each stroke maintains its own state—(1) not yet scheduled for execution, (2) scheduled but not yet executed, (3) currently executing, or (4) already executed—which a web socket passes between the design tool and CNC machine. Once strokes are authored and sent, LINC generates toolpaths and machine code for CNC machines to paint or engrave on the original object (see Figure 1 b & d).

To fabricate artworks in 2D, we used a Shopbot Full Size (8 by 4 feet) PRSalpha CNC. We augmented the Shopbot with a custom wireless mechanized pen tool that holds two large acrylic markers which can be independently raised or lowered during drawing. To decorate existing objects in 3D, we used a Handibot with a rotary axis extension. Since objects need to be physically fixated

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Figure 2: Left: Three marker drawings by the 2D system leveraging computational design tools and demonstrating variable stroke width. Right: A piece of driftwood, wax skull, and toy train engraved by the 3D system.

in a predictable, stable position during engraving, we procedurally generate 3D-printable mounts using constructive solid geometry operations. Figure 2 shows author-created objects.

3 EVALUATION

In evaluating our framework, we were interested in comparing the advantages of static versus live ("live" defined as both manual mode and ASAP mode) authoring modes, 2D versus 3D fabrication experiences, as well as gathering qualitative feedback on our design tool. We recruited eight participants (five female) with prior experience in art and design to create artworks using our system. Participants first spent 30 minutes with the 2D system, and then 30 minutes with the 3D system. Each of these sessions consisted of a short exploratory period, when participants acquainted themselves with the design tool's interface and feedback cycle, and a longer unrestricted creative session, when participants chose both what to draw and which authoring mode to use. Participants drew on white paper using the 2D system, and decorated a wooden cylinder and Dunny figurine using the 3D system (see Figure 3). They were asked to think aloud and provided additional feedback in a post-survey.

Overall, participants found LINC better matched for 2D drawing tasks, and all participants chose to use the live mode controls during their unrestricted creative pieces. Within the live mode controls, *manual* mode better allowed reflection-in-action while *ASAP* mode enabled greater initial exploration.

All participants agreed that both the static ($\mu_s : 4.4, \sigma_s : 0.5$) and live ($\mu_l : 4, \sigma_l : 0.8$) modes were easy to get started with. However, static mode was easier to control ($\mu_s : 4.3, \sigma_s : 0.5$) and make desired edits in ($\mu_s : 3.7, \sigma_s : 0.9$) than live mode ($\mu_l : 3.9, \sigma_l : 1.1$) and ($\mu_l : 3.1, \sigma_l : 1$), respectively. While every participant agreed that the 2D interface was well-suited for drawing on a large surface ($\mu_{s,l} : 4.4; \sigma_s : 0.7, \sigma_l : 0.5$), they felt the 3D interface was less well-matched for its task ($\mu_{s,l} : 2.9, \sigma_{s,l} : 0.6$); one cited the "a mismatch between the digital and physical artifacts" causing cognitive overhead and distance in the 3D interface.

A majority of participants said that live mode enabled both creative opportunities and better integrated their existing practices ($\mu_l : 4.3, \sigma_l : 0.8$) compared to static mode ($\mu_s : 3.8, \sigma_s : 0.7$). One participant commented, "I liked the immediate reaction of the live mode as it more resembled actual drawing experiences." Others echoed this sentiment: live mode was "faster and had more control, so [participants could] see the output and reflect on what was next,"

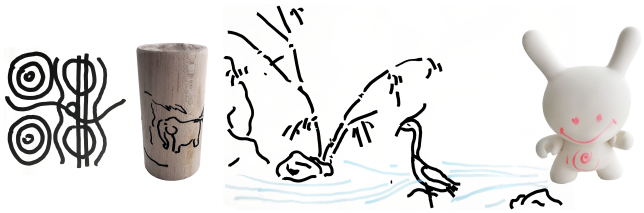

Figure 3: Final artifacts from our user studies. Left: Short exploratory sessions. Right: Open-ended creative sessions.

and "felt more like a coupled drawing experience, rather than the design and output workflow."

While executing their large-scale 2D artworks, four participants used manual live control, three ASAP, and one switched between the two. We saw greater opportunity for reflection-in-action in manual controls: two out of the four participants modified unsent strokes in their original drawings halfway through machine execution. Participants first executed some central, form-establishing strokes, similar to sketching guides, and then reshaped their artworks based on physical reactions or unexpected outcomes, such as pen colors blending together. The participant who switched modes also followed this workflow: they first manually executed the base structure of a tree, and then used ASAP mode for details like branches and leaves.

4 CONCLUSIONS

We present a framework for the direct and immediate drawing of 2D artworks and decoration of 3D artifacts, and developed LINC, a sketch-based design tool to realize this framework on modified CNC machines. By narrowing the gap between designer and fabricator, between human and machine, our system aims to support rich interactions absent from traditional forms of fabrication such as exploration, reflection-in-action, and immediate response to and revision of material outcomes and surprises.

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