Lucid Fabrication

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ABSTRACT
Advances in digital fabrication have created new capabilities and simultaneously reinforced outdated workflows. In my thesis work, I primarily explore alternative workflows for digital fabrication that introduce new capabilities and interactions. Methodologically, I build fabrication systems spanning mechanical design, electronics, and software in order to examine these ideas in specific detail. In this paper, I introduce related work and frame it within the historical context of digital fabrication, and discuss my previous and ongoing work.

Author Keywords
Digital Fabrication; Augmented Tools; Fabrication Workflows; Embodied Interactions

CCS Concepts
•**Human-centered computing** → **Human computer interaction (HCI);** *Interaction paradigms; Interaction devices;*

INTRODUCTION
Digital fabrication has transformed the ways in which engineers, designers, and artists create physical objects. Not only has it empowered diverse maker communities with the practical benefits of rapid on-demand fabrication, it has engendered new mediums for creative expression through unique manufacturing capabilities. Simultaneously, the workflows embedded in these fabrication tools have narrowed the ways in which we interact with and conceptualize fabrication, reducing a deeply hands-on process to keyboard and mouse interactions followed by a press of the 'print' button.

Researchers in HCI and beyond have approached these questions from a variety of perspectives — previous works have augmented hand-held tools with sensing and actuation [8], extended direct manipulation to physical making [7], and critically challenged the delegative interactions of existing workflows [1].

The contributions made in this space can be viewed hierarchically (Figure 1). Does the work primarily contribute a new

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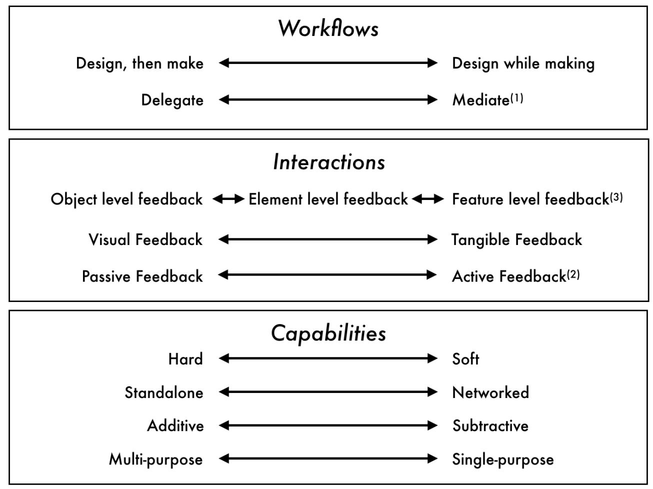

Figure 1. Related work in digital fabrication can be viewed in a hierarchy of capabilities, interactions, or workflows. Spectrums within this hierarchy have been proposed by Devendorf et al. [1], Gannon et al. [2], and Mueller [3].

capability (e.g. enabling the digital fabrication of new materials like fabric or glass)? Does the work primarily contribute new interactions for working with these capabilities (e.g. giving a user visual feedback or giving a user tangible feedback)? Or does the work primarily contribute a new workflow (e.g. design and making thought of as distinct stages, or as part of one process that can happen simultaneously)? The same capability of a digital fabrication tool can be utilized in drastically different systems embodying disparate interactions, divergent workflows, and opposing goals. This hierarchical lens aids in understanding the novel contributions of the rich, overlapping, and multidisciplinary work within digital fabrication.

Questions around how to engage with the capabilities of digital fabrication have been asked since the inception of numeric control (NC) in the mid-20th century. Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) software pipelines have emerged as the dominant way of controlling digital fabrication tools, and the historical inertia of this presumed workflow is felt throughout the current landscape. However, one of the earliest technologies proposed for controlling NC tools allowed a machinist to define a toolpath by manually cutting the first part. The actions are recorded and replayed for subsequent parts, in a process called Record-Playback [4]. One primary distinction of this workflow is that rather than attempting to tighten the interaction loop of programming and machining, the embodied actions of manually machining *is* the programming. We are inspired by this seminal work to further consider how computation can augment and extend a user's capabilities during the process of making. My previous and proposed research focuses on examining new workflows that attempt to address this primary research question:

> *How can digital fabrication tools engage and amplify opportunities for human judgment, skill, and creativity during the fabrication process?*

Through this lens, I develop systems which elevate the capabilities of makers with novel fabrication tools that work in unexplored materials and contexts, leverage our capacity for embodied cognition during the design and fabrication process, and engage broader audiences by inverting the presumed ways of working with these technologies.

LUCID FABRICATION

This dissertation title references the experience of lucid dreaming. When we sleep and dream, we are often passive observers with limited agency, even though the dream we are experiencing is our own. Operating modern day digital fabrication equipment can be similarly disorienting, in which after the initial set up of the fabrication task, we are left to watch idly, maybe waking up suddenly after some disastrous failure of the part, machine, or both. Lucid fabrication seeks to create workflows which reimbue users with agency during the fabrication process — agency of design, expression, feedback — which respect our capacity for embodied knowledge to skillfully and keenly respond during the process of fabrication.

In my first two projects, I addressed this theme from complementary perspectives. Whereas *MatchSticks* was primarily concerned with enabling users to more fluidly communicate their design intent, *Turn-by-Wire* focuses on the feedback that a user can receive from the tool during the process of fabrication. Lastly, I propose a project involving robotic fabrication which generalizes and expands upon these ideas.

MatchSticks

Woodworking through Improvisational Digital Fabrication

MatchSticks explored how the accuracy and precision of a CNC machine can be interacted with as directly as a hand tool (Figure 2) [6]. This idea was developed in the context of wooden joinery, the fundamental building block of furniture and other wooden structures (Figure 4). Whereas traditional CNC machines require users to navigate a gauntlet of software tools before anything can be fabricated, our system allows users to rapidly specify their design intent — the type of joinery connecting two pieces of wood — through a touchscreen interface mounted directly to the CNC machine (Figure 5). This resulted in a workflow similar to that of a miter saw: a user can approach the machine with their material, select a joint, indicate the size of their wooden material, and immediately create that joint. Though the *MatchSticks* system is not literally a tool which that is held by hand during operation, the ability to directly articulate design intent captures a core attribute of hand tools usage. This work contributes a custom CNC machine designed to suit the unique geometric

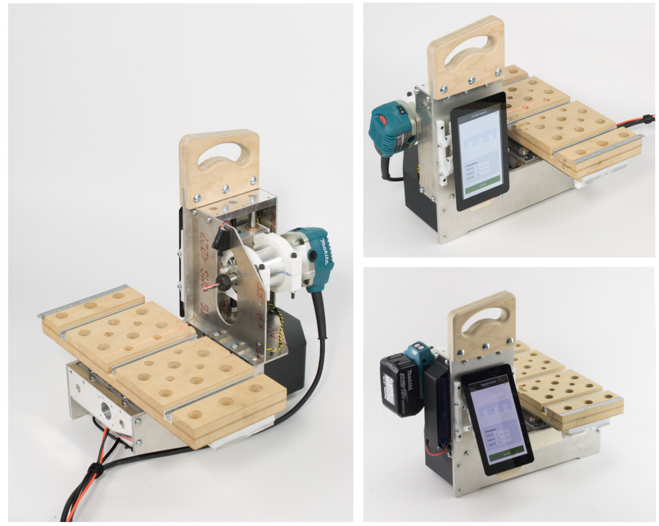

Figure 2. MatchSticks consists of a 3-axis CNC machine, trim router, touch screen for user interaction, line laser for quickly and accurately aligning cuts, and a modular build bed that accepts a variety of fixtures and alignment pins. During wireless operation, the motors run from a LiPo battery and a battery powered trim router is used.

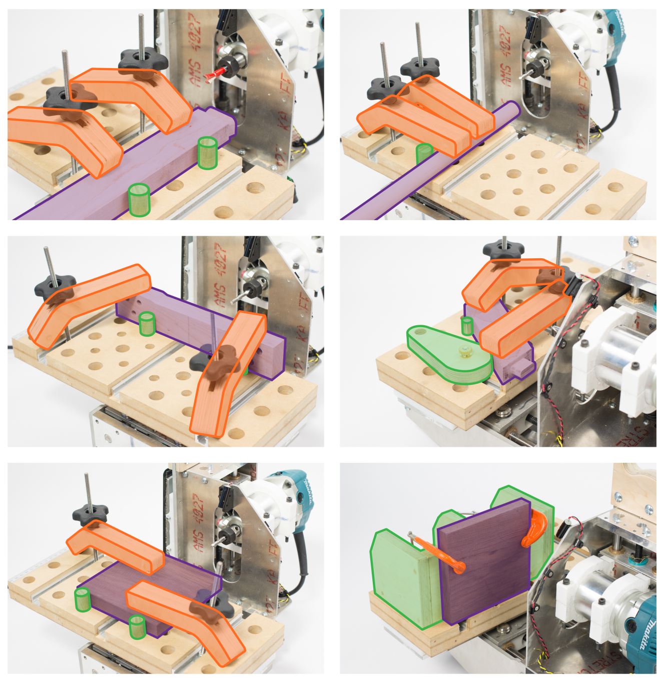

Figure 3. One strength of our machine tool is its ability to rapidly fixture components in a variety of orientations. This allows us to create geometries that would be substantially more difficult to create because of physical constraints such as undercuts. Left to right from top left: using our system, machining can occur at the ends of lumber, on round stock material, across edge profiles, at angles, in-line with the edge of a board, and on the surface of boards. This is made possible by modular components for fixturing (orange) and alignment (green). Workpiece shown in purple.

Figure 4. Three styles of joints (with topologies resembling the shape of the letters X, T, and L) are used in combination to create this table. All pieces used in this table are longer than any dimension of our CNC tool.

Figure 5. Participants in a user study used our system to create a parametric frame, one of the primary building blocks of furniture making.

constraints of fabricating joinery (Figure 3), and a similarly focused software pipeline designed to support more fluid ways of working with digital fabrication tools. Participants in a user study responded positively to our tool, commenting on the flexibility of this alternate workflow, and how it challenged their perceptions of joinery as prohibitively difficult or intimidating.

MatchSticks allowed users to interact with a digital fabrication tool more directly, but these interactions were primarily one directional. Users are empowered to quickly specify their design intent, while materials and tools are viewed as passive objects that design intent is imposed upon. Recognizing this gap, the next project explores how the 'feel' of the tool during use can be communicated directly to the user through haptic feedback.

Turn-by-Wire

Computationally-Mediated Physical Fabrication

Digital fabrication is often narrowly framed as the process in which a computer controlled machine physically renders a geometry created in software. This work instead explores how a deeply hands-on physical fabrication process can be imbued with the affordances and advantages of digital authoring [5]. We implement these ideas in a lathe, a machine tool in which cutting tools move about a rotating piece of stock material to cut it to the desired shape (Figure 6). Cylindrical geometries such as chess pieces are often created on these machines (Figure 7). Situated between the mechanical couplings of a manual lathe, and the disembodied control of a CNC lathe, *Turn-by-Wire* directly and digitally couples the user to the tool through haptic feedback handwheels that control the lathe in a "drive-by-wire" configuration. This work primarily contributes the

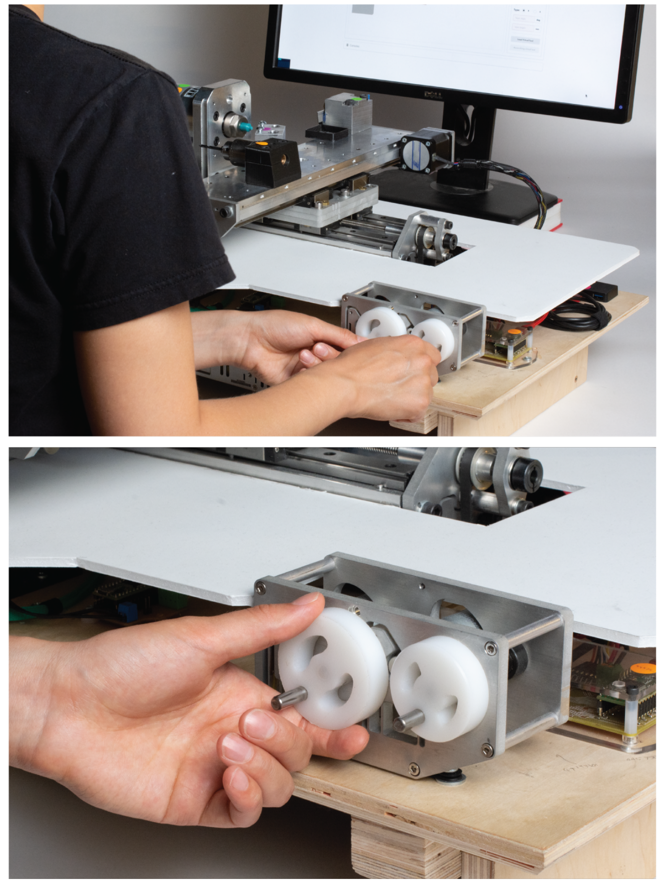

Figure 6. Top: the *Turn-by-Wire* system consists of a lathe, handwheels, and GUI. Bottom: detailed view of the haptic feedback handwheels used to directly control the lathe.

Figure 7. Lathes are uniquely suited for fabricating cylindrical geometries. From right to left: nesting dolls, bowling pins, top, chess rook, and energy dome.

Figure 8. Left: User study setup with lathe, handwheels, and computer monitor to display the GUI. Right: Widgets made by the five expert fabricators during the user study.

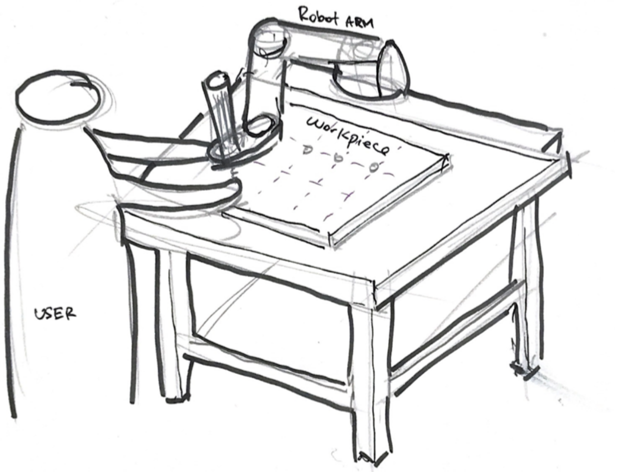

Figure 9. A robotic arm is used as a haptic exoskeleton that can enhance a user's accuracy or safety during the process of fabrication.

concept and implementation of a richer set of haptic feedback that mediates a user's interaction with a fabrication tool. These haptic interactions are not limited to literal representations of feeling a desired model or imitating the forces experienced by a tool — any type of coupling and feedback can be designed and implemented to augment and mediate the experience of using this tool. In this work, we leverage haptics to empower users to communicate intent, perceive state, and acquire technique during the fabrication process. For example, a user can 'snap-to' a haptic guide, amplify the forces felt by a delicate cutting tool, or learn a new technique through haptic feedback. In addition, this project investigates workflows in which the division between design and fabrication is amorphous. The physical act of machining a part using *Turn-by-Wire*, mediated by interactions for expression and feedback, is also the process for designing a model in-situ of the manufacturing constraints required to fabricate it. We evaluate our system with five expert fabricators who found value in both the specific haptic interactions as well as the overall workflow (Figure 8).

ROBOTIC FABRICATION (IN PROGRESS)

In current work, I am exploring how the ideas embodied in the previous two projects can extend to one of the most general fabrication tools — robotic arms. Specifically, I want to explore how users can use a robotic arm as a haptic exoskeleton to experience digital affordances such as snap-to-grid for any physical fabrication process. This generalizes the ideas behind *Turn-by-Wire* by infusing the "by-wire" control directly to the user, rather than to a particular machine. Again, rather than interactions guiding the user towards any particular outcome, computation is leveraged to augment the *process* of fabrication. In addition, I want to further explore how the fabrication process can further gravitate from characterized by delegation to one of collaboration. Who or what else might have control over these final fabricated artifacts, and how might this control reciprocate between these various agents? In addition, how might these machines exhibit personality, gesture intention, or communicate uncertainty, to collaborate with us in more personal and expressive ways?

DISSERTATION STATUS

I plan to submit my dissertation within one and a half years. Feedback in the doctoral symposium would be highly valuable for guiding direction the last project and to sharpen the overall narrative of the dissertation.

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