Jubilee: An Extensible Machine for Multi-tool Fabrication

Joshua Vasquez, Hannah Twigg-Smith, Jasper Tran O'Leary, and Nadya Peek
University of Washington, Seattle, WA, USA
{pomnut, htwigg, jaspero, nadya} @uw.edu

ABSTRACT
We present Jubilee, an open-source hardware machine with automatic tool-changing and interchangeable bed plates. As digital fabrication tools have become more broadly accessible, tailoring those machines to new users and novel workflows has become central to HCI research. However, the lack of hardware infrastructure makes custom application development cumbersome. We identify a need for an extensible platform to allow HCI researchers to develop workflows for fabrication, material exploration, and other applications. Jubilee addresses this need. It can automatically and repeatably change tools in the same operation. It can be built with a combination of simple 3D-printed and readily available parts. It has several standard head designs for a variety of applications including 3D printing, syringe-based liquid handling, imaging, and plotting. We present Jubilee with a comprehensive set of assembly instructions and kinematic mount templates for user-designed tools and bed plates. Finally we demonstrate Jubilee's multi-tool workflow functionality with a series of example applications.

Author Keywords
Digital Fabrication, Toolchanging, Multi-tool Workflows

CCS Concepts
•Human-centered computing → Interactive systems and tools; •Applied computing → Computer-aided manufacturing;

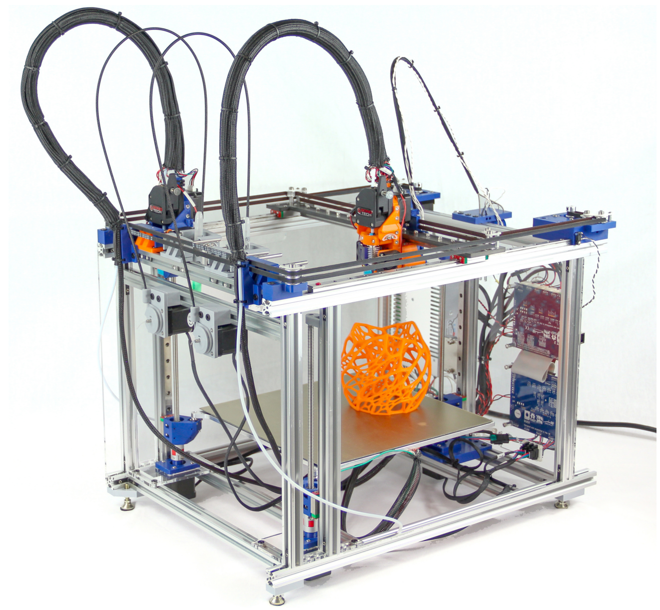

Figure 1. Jubilee is a multi-tool machine that can automatically change user-developed tools. Shown with a 3D printer tool installed.

INTRODUCTION
HCI researchers are increasingly developing computer-driven tools for application spaces such as fabrication, biology, or materials. For example, Teibrich et al. presented a tool that allowed for removing and re-making parts of 3D printed objects [41]. Gome et al. presented OpenLH, a tool for creative exploration with biological liquid handling [13]. Rivera et al. explored HCI aspects of soft and rigid material printing with their Desktop Electrospinning tool [37]. Each of these examples is part of a larger trend in HCI research around physical processes such as manufacturing, analytical instrumentation, and laboratory science experimentation.

Of particular interest to HCI are *multi-tool processes*, which make use of multiple tool heads controlled by a common *motion platform*. A motion platform is anything that enables programmable motion along one or more axes; in this case, it is the rest of Jubilee's frame besides the tools and the bed (shown in gray in Figure 2). While multi-tool processes are not yet commonplace, one example of a multi-tool workflow is multicolor 3D printing. In a multicolor 3D print, the 3D printer will control two or more extruders, tools which take turns extruding filament, with the end goal of having different parts of the model printed in different colors. The 3D printer automatically switches between the different extruder colors. Automatic tool-changing enables multiple colors to be used at each layer of the 3D print without manual intervention.

Generalizing beyond 3D printing, we envision many novel fabrication workflows that could only result from the repeated, sequential exchange of multiple tools. If an artist wanted to plot a drawing using many colors of pens, they would be able to control the machine to pick up a different colored pen for each color in the drawing. A biologist could control multiple

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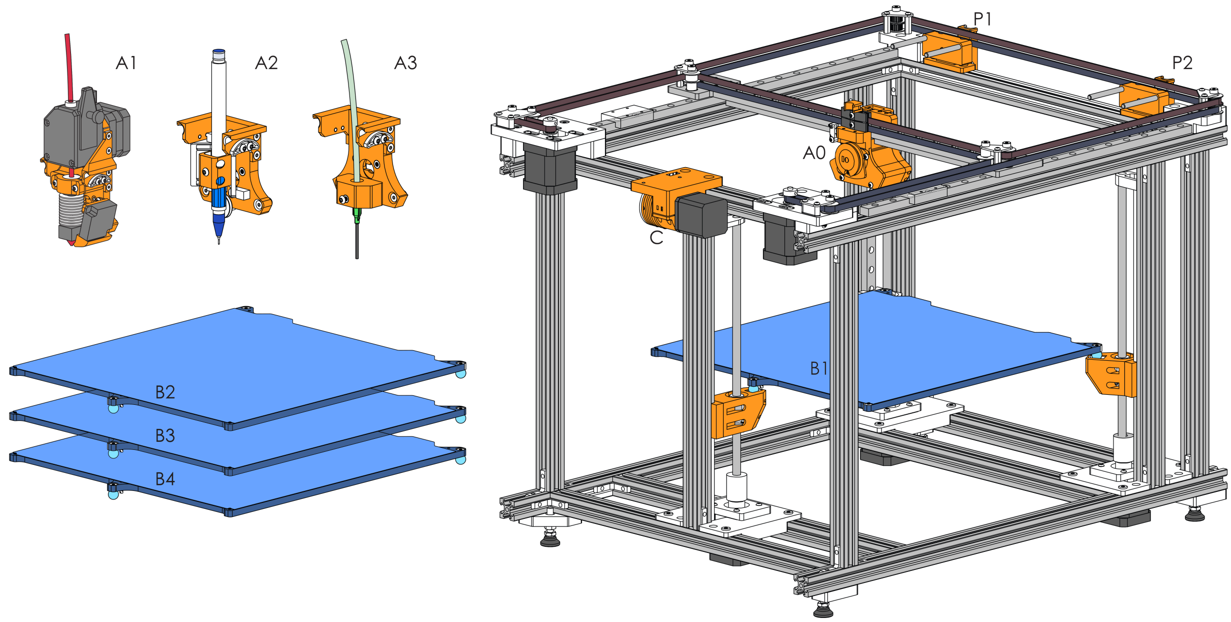

Figure 2. Jubilee, an extensible machine for multi-tool fabrication. Tools, top left, include a (A1) a 3D printer extruder, (A2) a pen holder, and (A3) a syringe dispenser. The tools are picked up by the carriage (A0), from (P1, P2) parking places. The tools are locked with the (C) lock assembly. The beds (B1-B4) are interchangeable.

syringes to deposit controlled mixtures of two solutions over several wells in a well plate, wait for any reactions to occur, and then carefully control a microscope to image the results. Without the ability to change between syringes and the microscope, or between different pens, such interactions would not be possible. We argue that multi-tool workflows are an important, yet underexplored space for interesting interaction. With support for multiple tools and automated tool-changing, digital fabrication machines could become more appealing to practitioners from emerging domains.

The present work aims to support an HCI research trajectory into physical processes by providing an extensible platform for executing multi-tool processes. Currently, creating novel fabrication processes is partially limited by the researcher's ability to create new machines. Adding new tools to existing machines is one way to achieve this, as is e.g. done by Hudson for felting teddy bears [18], but there is a limitation to the number of tools a single machine can support at once. End-user facing machines that allow for changing of the heads, such as Wang et al.'s xPrint system or Peek and Moyer's Popfab [47, 29], still require the change to be performed manually.

We see value in HCI researchers exploring novel workflows that use multiple tools in an automated process. However, building machines for multi-process workflows requires design expertise, which excludes contributions from researchers and practitioners without such knowledge. What tools can support the development of novel multi-process workflows without requiring such expertise? More precisely, our research question is: *How might we enable a broader community of domain experts to develop novel multi-tool workflows?*

Towards this goal, we contribute:

- Jubilee, a fabricatable open-source hardware machine that automatically changes tools,
- a standard mechanical pattern for user-developed tools to attach to Jubilee
- a series of custom tools and demonstration applications that demonstrate Jubilee in various multi-process workflows
- a bed plate that can be removed and reinstalled repeatedly without requiring manual repositioning.

RELATED WORK

Our research relates to existing work in fabrication, machine-controlled processes, and HCI. In this section we summarize what we see as key work in the area and describe our difference in approach.

Fabrication and HCI

Proponents of *personal fabrication* anticipate that fabrication will soon become as widely available as computing [12]. During the workshop Fab@CHI, Mellis et al. [25] outlined opportunities for fabrication and HCI, such as end-user design tools, STEAM education possibilities, and personalized objects and interfaces. This extended prior concepts, including *Interactive Fabrication*, affording users real-time interaction with machine control, by Willis et al. [49] and *Pervasive Fabrication*, extending pervasive computing to include education fabrication, by Eisenberg [9]. Baudisch and Mueller have since outlined an agenda for personal fabrication and HCI where they includes materials and machinery [3]. This research all anticipates the influx of many new users to fabrication who are markedly different from industrial practitioners.

Understanding the needs of these fabrication newcomers has been the topic of HCI research. Devendorf and Ryokai explored designing for particular qualities of user experience in *Being the Machine* [7]. Jacobs and Zoran transported digital fabrication tools to a rural hunter-gatherer community to explore what these tools would mean for their traditional craft [20]. Quitmeyer and Perner-Wilson developed a fully portable, wearable fabrication studio for harsh environments, exploring the possibility of fabrication in remote locations [35]. Hudson et al. observed exactly what happens when 'casual' makers engage with digital fabrication [17]. Questioning the promises and practices of HCI's Making Agenda, Bardzell et al. ask *"how emerging technologies can support more inclusive, democratic, and (truly) empowering making practices"* [2].

Adding to this work, our research also considers the HCI implications of fabrication being adopted by new user groups. Our contribution considers how newcomers, given a very different context for fabrication, also might require different kinds of (inclusive) fabrication infrastructure. In particular, we seek to allow newcomers to create their own tools and multi-tool workflows. As such, we present a machine design that provides common case hardware capabilities, freeing the user to focus on designing the tools according to their own needs.

Novel HCI Machines

Developing workflows for novel applications in fabrication is an active topic in HCI research. We mention printing with soft materials and electrospinning in our introduction [47, 18, 37]. Fabricating electromagnetic coils directly on 3D prints is demonstrated in [30]. Wireprint, On-The-Fly Print, Laser-Stacker, and Fabrickation aim to speed up the production of 3D objects by using digital fabrication machines in different ways [27, 32, 45, 28]. Revomaker and CoFiFab aim to speed up 3D printing by starting from interior mandrels [11, 39]. RoboFDM aims to reduce support material by adding degrees of freedom to the printer [50]. These workflows are all developed by modifying existing machines (mostly off-the-shelf 3D printers). Our research aims to contribute a machine designed *for users* to make these kinds of modifications.

Developing novel machines for novel workflows is also an active topic in HCI research. The Cardboard Machine kit breaks components of digital fabrication machines into simple modules, so that users can assemble those into their own machines [29]. FreeD is a hybrid sculpting tool that combines hand-held and automated milling using position sensing [52]. Shaper Origin is a hand-held CNC milling tool that uses computer vision for its position sensing [38]. Peng et al. presented a novel machine that creates objects out of layers of fabric [31]. Matchsticks is a tool that uses localized computer control to create common woodworking joints [42]. Popfab explores portable digital fabrication, by combining a general-purpose motion platform that fits within a suitcase with changeable tool heads [29]. Our work aims to lower the barrier in creating robust novel machines by abstracting away much of the hardware related to tool motion.

Industrial Tool Changing

Automatic tool changing systems are common among high end industrial manufacturing machines. However, machines equipped with tool changing systems are typically limited in scope to subtractive manufacturing, where all tools are generally centered around various means of material removal from a stock material (e.g. Haas [15] and Datron [6]). Robotic arm tool changers are another high end industrial solution, limited to a small set of high-performance applications (e.g ATI Industrial Automation [1]). In contrast, our work seeks to bring tool changing to novel workflows and applications, such as those that are already being explored in HCI research.

Materials and HCI

Materials science research could be very interesting for HCI applications, but we do not yet have the tools to harness these advances. Functional inks for 3D printing have been introduced in materials science, for example for 3D printing cellular composites [5], printing metal at low temperatures [46] or high-performance battery geometry [40]. Bioengineers have successfully 3D printed with living cells [14], and designers have explored transforming structures in 4D printing [43]. These advances in materials enable HCI researchers to develop novel interactions and user experiences, such as Wang et al.'s flat-packed transforming pasta [48], the shape-changing interfaces of PneUI [51], or metamaterial mechanisms [19]. Qamar et al. provide an overview of how material science can inform HCI research [34], but underline that lack of equipment prevents HCI research from engaging more deeply. Our research aims to provide equipment for HCI researchers in support of computationally controlled material explorations.

JUBILEE DESIGN OBJECTIVES

Jubilee is a computer-controlled machine, with XYZ motion and a variety of tools (also referred to as heads or end effectors). Jubilee is open-source and designed with the following high level design goals:

- Tool-changing: automatically picking up and using different end effectors
- Single-Quantity Reproduction: feasible and inexpensive for users to build on their own in quantities of one
- Extensibility: easy for user to add new functionality

To achieve these goals, we contribute several design patterns.

Separation of Concerns

Separation of concerns is a principle from object-oriented programming for writing modular code. We apply this principle to the mechanical design of our motion platform such that functionality for specific tool is completely separate from the system that provides motion. For example, an extrusion 3D printer extruder tool requires specialized parts including the extruder itself, a hot-end fan, a part-cooling fan, a bed heater, and temperature sensor peripherals. While some of these specialized parts could be mounted to the motion platform frame and shared between tools, we instead keep such application-specific functionality physically attached to the swappable tools and beds. This provides an application-agnostic means for users to add tools for new interactions. Adhering to this principle helps users who want to extend Jubilee with custom tool heads. Instead of having to design an entire machine, the user only needs to design the application-specific tools.

Fabricatability

We want domain experts such as HCI researchers to be able to use Jubilee as a platform for multi-tool workflows. To make DIY replication more accessible, we designed Jubilee for single-quantity reproduction. Specifically, we have designed Jubilee according to *fabricatability* principles: namely, its total price does not rely on volume discount pricing of parts, it can be made with readily available equipment, and all the knowledge needed for assembly is described in the documentation. Jubilee is composed of parts that are either readily available in single quantities or fabricated through 3D printed or laser cut processes on equipment common in makerspaces. These design goals are in line with prior instances of fabricatable machines such as the Fabricatable Axis [10]. An example of a fabricatable component, made with off-the-shelf and 3D printed parts, is shown in Figure 3.

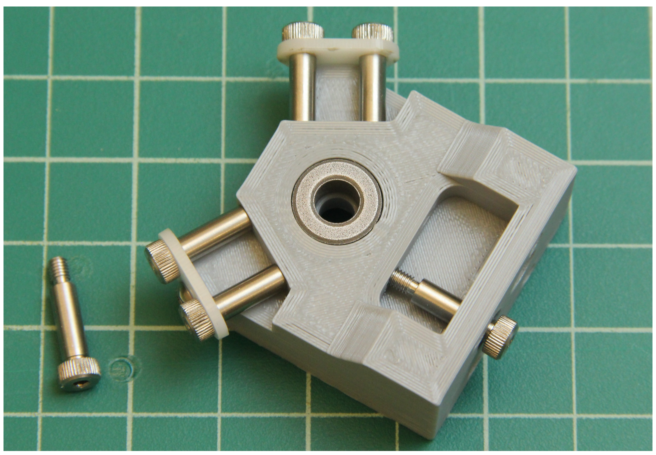

Figure 3. A fabricatable mount made using either off-the-shelf parts (e.g. the screws), or parts that can be made on inexpensive digital fabrication machines such as 3D printers (here the gray plastic part).

Exact-Constraint Design

As tools are picked up and dropped off over the course of a machine task, it is critical that their position with respect to the motion platform carriage remains consistent. In this way, Jubilee may pause any tool's process, park the tool, pick it up again, and then resume the process from a known location. By following *exact-constraint* design principles [4] for connecting physical parts, we ensure that components will be removed and reinstalled in an extremely repeatable manner (typically with a repeatability below 40 μm). Connectors built with these principles are called *kinematic couplings*, and they avoid mechanical issues such as binding or play. Kinematic couplings are well-known in the field of optics for aligning precision optical equipment, but they are not commonly used in machine design. We use exact-constraint design principles to design kinematic couplings for any removable parts of our system.

These design goals of separation of concerns, fabricatability, and exact-constraint design have informed our implementation of the tool changer, the motion platform, and the materials we used. We will give further details on the implementation in the next sections.

TOOL-CHANGER IMPLEMENTATION

Depending on tool size, Jubilee can hold approximately four to six idle tools at once in parking slots, which can be picked up by the tool carriage to be moved around in the machine. The tools are positioned on the carriage using a coupling, then locked using a lock assembly. Details of the tool-changing implementation are provided in this section.

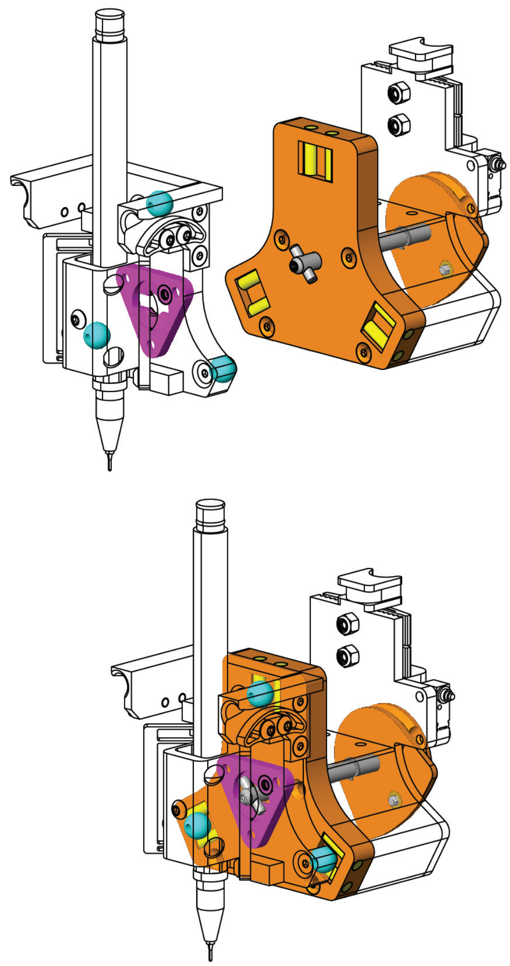

Figure 4. The tool carriage (shown on the machine in Figure 2 A0) presented with an example pen tool shown in unmounted (above) and mounted (below) states. Steel dowel pins on the carriage (yellow) and steel balls on the tool (blue) provide the six points of contact and form a kinematic coupling. The wedge plate (pink) connects to the twist-lock (grey).

Tool Coupling

When controlling tools with Jubilee, we need to first tell Jubilee's control system where the tool is relative to the machine frame. Because tools are removable, we can avoid recalculating these values by using a connector, or tool coupling, that places the tool in the exact same position every time it is attached. To achieve this, we apply exact-constraint design principles to the interface between carriage and coupling.

The Maxwell Coupling is an exact-constraint kinematic coupling where two separate parts are held together touching only at six points of contact, pushed together with a nesting force. Each point of contact constrains a spatial degree of freedom [4]. When the two elements are joined in this fashion, the mechanism is referred to as *perfectly constrained* since the number of degrees of freedom matches the number of constraints. Our coupling uses three grooves (on the tool carriage) and three balls (on the tools) for six points of contact, constraining motion in XYZ as well as in roll, pitch, and yaw (shown as solid colors in Figure 4). Adding supplementary constraints *overconstrains* the two components and can introduce either mechanical binding or mechanical play between the two components. Adding fewer than six constraints *underconstrains* the coupling, enabling the elements to move relative to each other along the unconstrained degrees of freedom.

This design is geometrically similar to the coupling used in Peek and Moyer's Popfab machine [29] and is designed for compatibility with the coupling used by the 3D printer original equipment manufacturer E3D [23]. However, our implementation is novel in that this coupling is made from a majority of off-the-shelf and 3D-printed components that do not require any specialized machining processes.

Lock and Unlock

Tools are positioned on the carriage (shown in Figure 2A0) with the kinematic coupling. While this coupling positions the tool precisely into the carriage, it does not secure it in place. This is accomplished by pushing on the tool with an additional force called a *nesting force*. This nesting force is provided by a *twist-lock* shaft, shown in gray in Figure 4, which twists onto the *wedge plate*, shown in magenta in Figure 4. The twist-lock shaft has a pin which is pushed up the helical wedge, locking the tool in place. The wedge plate is designed to be replaceable, as it will degrade over thousands of tool-changing cycles. The twist-lock is actuated by a motor driving two flexible mechanical control cables controlling a pulley, shown in Figure 2 as C and A0. These control cables work similarly to a bicycle brake cable. Pulling one control cable rotates the twist-lock into the wedge, causing it to lock the tool. Pulling the other cable releases the twist-lock from the wedge, in turn, releasing the tool. By using a cable, we can move the actuating motor off of the carriage, reducing the weight of the carriage which improves the overall performance. The control cables are sheathed in a cut-to-length extension spring called *spring guide*. We have cycle tested the tool lock/unlock system and found it to be reliable for at least 2000 tool changes without intervention.

As a tool's wedge plate degrades with each lock/unlock cycle, the tool will properly lock at a different angle of the twist-lock shaft. Furthermore, several tools will be in use at once, each of which is at different stages of their wedge plate's life cycle. Therefore, reliably locking tools requires a torque-based locking solution rather than a position-based locking solution. To solve this constraint, we designed a *lock actuator*

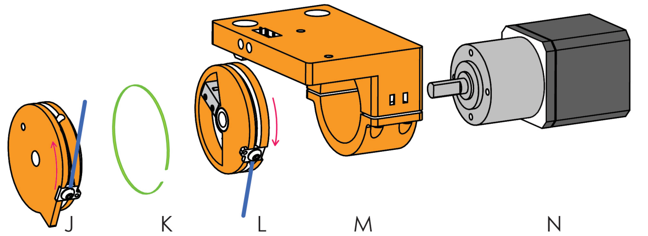

Figure 5. An exploded view of the *lock actuator* subsystem. The left pulley (J) is fixed to the motor shaft (N) while the right pulley (L) can freewheel. Both pulleys are joined by an extension spring (K). When a tool locks on the wedge plate, it puts the right cable in tension, stretching the spring, and triggering an internal limit switch (inside pulley L, grey). Assembled, the lock actuator can be seen on the machine in Figure 2 C.

subsystem, shown in Figure 5. This subsystem senses the torque and ensures that the lock adheres to a torque limit.

The *lock actuator* subsystem, labeled C in Figure 2 and exploded in Figure 5, is a series-elastic actuator [33] where two stacked pulleys (Figure 5 J and L) connected by a spring (Figure 5 K) provide both the means of actuating the control cables and detecting a locked tool. Pulley J is fixed to the shaft while pulley L is free-floating and tied in series to Pulley J through an extension spring. Locking and unlocking are closed-loop operations detected by two limit switches. Unlocking is sensed by rotating the pulleys to a fixed position while locking is only sensed after stretching the spring by a small angle fixed in the design. Together this small "stretch" angle and the length of the spring set the torque limit at which tools will lock. This design is similar in concept to an analog torque wrench used for screwing fasteners to a fixed torque limit.

Tool Template Pattern

Tools are derived from a standardized tool plate pattern which fixes the locations of both the steel coupling balls and the wedge feature for locking tools as shown in Figure 6.

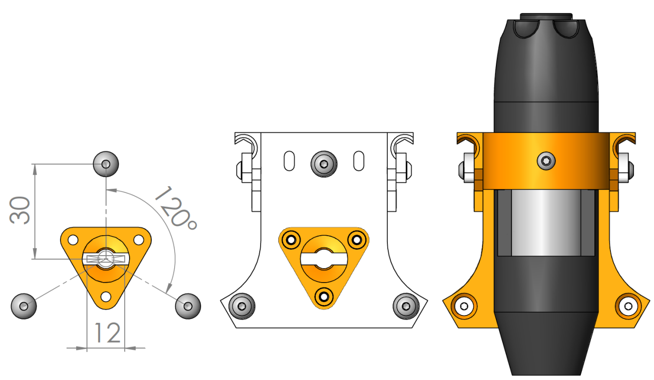

Figure 6. Creation of the USB Microscope Tool from the base tool template. Design starts by adopting the tool ball and wedge plate pattern into a plate, adding two "wing" features for parking, and finally mounting the primary tool components to the plate.

Creating a custom tool requires combining the user's application-specific parts with the tool plate template. The tool template shape can be resized within some limits so long

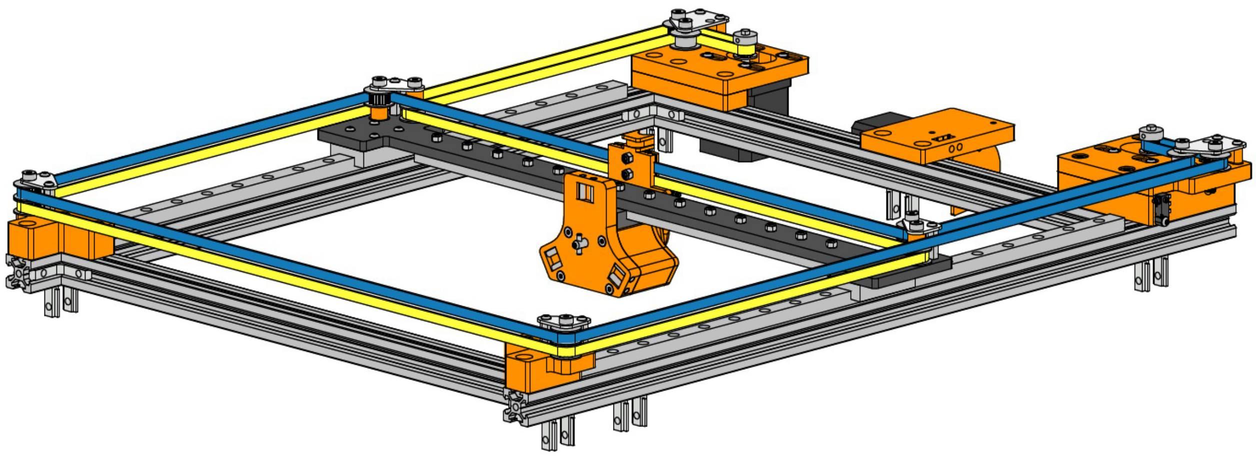

Figure 7. ***Flush-Form*** **CoreXY belt pattern as mounted on the XY frame of Jubilee. The pattern consists of both an upper (blue) and lower (yellow) length of open belt joined at the center carriage.**

as the location of the coupling balls and wedge feature are preserved. Detailed instructions on extending Jubilee with custom tools, including space constraints, are described in the project repository.

MOTION PLATFORM IMPLEMENTATION

Jubilee's tools can travel along XYZ degrees of freedom in a work envelope of 300x300x190 mm making it comparable to a medium-sized desktop 3D printer. Key features of our motion platform implementation include both a hot-swappable bed platform and a drive train which uses a novel CoreXY implementation.

Kinematically Coupled Bed Platform

In adherence to the separation of concerns design principle, Jubilee's bed platform is removable. In Figure 2, the removable beds are labelled B and shown in blue. Users can develop custom bed platforms with features specific to their applications. For example, a user could design a bed to hold standardized 96-well or Petri plates in a fixed position. That bed would eliminate the cumbersome task of aligning the well plate to the machine as the custom bed plate holds the well plate in predefined, fixed locations.

Furthermore, like Jubilee's tools, the bed is kinematically coupled to the frame, enabling it to be removed and replaced across thousands of cycles without losing registration to the machine. Three spheres on the base of each bed plate nest onto three slots driven by the Z-axis motors, creating another instance of a Maxwell coupling. This feature creates a *transfer mechanism* between human and machine where the bed platform may be exchanged between the two mid-process [16, 21]. Consequently, a machine process can be paused midway, the plate removed, and then reinstalled and resumed without re-homing. This feature enables novel workflows where the user might want to apply a process to the objects on the bed outside of the machine. For instance, in 3D printing, the user can pause the printing process and remove the bed plate to embed magnets into the partial print. When finished, they may reinstall the bed plate and resume printing. Alternatively, in growing cells, the user could remove a bed plate with cellular media from an incubator and install it into Jubilee for imaging with a microscope tool. When finished, they may remove the bed plate from the machine and place it back into the incubator. By repeating this process over many hours, they are able to capture images of growing cells without needing to search for the cell at each imaging step. In short, many other processes can occur outside the confines of the machine frame by temporarily removing the bed platform without loss of precision.

Flush-Form CoreXY

The kinematics of the motion platform are implemented with three leadscrews driving the Z-motion, and a timing belt driving the XY motion with a parallel kinematic design. Parallel kinematics are a good choice for high-speed movement in the XY-plane as they enables faster carriage accelerations than a typical Cartesian gantry by reducing the moving mass by one motor.

Specifically, Jubilee implements a modified *CoreXY* belt pattern [26, 29]. This novel Flush-Form CoreXY affords easier installation and tuning than a traditional CoreXY belt pattern. It simplifies both the belt installation and belt tensioning steps, which conforms to our fabricatability design goal. The belt routing is shown in Figure 7.

Our *Flush-Form* CoreXY pattern modifies the pulley placement in the original belt pattern by stacking both sections of belt vertically along the entire length of the belt. This modification preserves the original kinematics but provides a more intuitive assembly setup as the two belts more closely follow the same pattern. Furthermore, this change simplifies belt tensioning by moving the tensioner to a more accessible location. In our design, both drive motors are seated into slots, and the belts are tensioned by adjusting their position by turning a set screw (shown in Figure 8).

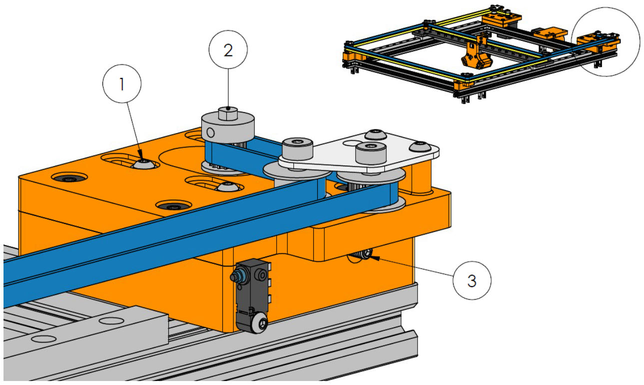

Figure 8. (1) Slot features for motor positioning, (2) Drive Pulley mounted on one of the x-y stepper motors, and (3) Set Screw for adjusting the belt position.

TOOL IMPLEMENTATIONS

Along with the tool changer and motion platform, we also provide designs for several canonical tools (including 3D printer extruder, pen, and liquid dispenser), shown in the upper left of Figure 2. Before executing a machine process, tools may be placed on parking posts at the front of the frame. Parking posts are dedicated to a specific tool, and their location on the frame (Figure 2 P1 and P2) is set in the software in advance. During a process the tool carriage changes tools by automatically releasing the active tool into its parking post and retrieving an idle tool from the set location. We discuss each tool in detail below. Use cases with these and other tools are discussed in Section 9, "Use Cases".

Extruder

We contribute an extruder tool for fused filament fabrication 3D printing, shown as A1 in Figure 2. This tool is composed from a direct-drive Bondtech BMG Extruder Drive, an E3D V6 hotend, and an onboard fan for part cooling. In addition to the drive, each tool includes a thin, silicone strip fixed to the frame at the parking location and used for cleaning the nozzle. Each time the carriage retrieves an extruder, it performs a back-and-forth wipe to remove any dangling melted filament left on the nozzle tip. Additionally, our current implementation prints both the desired part and a supplementary *priming tower*, a feature (shown in Figure 11) where each extruder deposits debris at the start of each layer to further remove any nozzle debris. With additional tuning to reduce the dribbling of idle extruders, this priming tower is staged to be removed from future implementations.

Plotter

We contribute a tool for pen plotting, shown as A2 in Figure 2. This tool can hold a single pen of various diameters. These pens are actuated up-and-down via a cable, similar to the mechanism for tool locking. While the pen could be developed without moving parts, actuating the pen directly dramatically increases the plotting speed.

Syringe

We contribute a bulk liquid dispensing tool, shown as A3 in Figure 2. It is implemented with a replaceable Luer-Lock style syringe tip and a peristaltic pump. Liquid is pumped from any liquid container to the tool tip through a long length of flexible tubing. This design choice mandates that users must first prime the tube before using the tool to remove the air. This tool is intended for either repeated or bulk transfer of a single liquid, which can be done at different speeds, in one spot or along paths, and in increments of 0.1ml. By installing several syringe tools, various types of liquids can be dispensed by dedicating one discrete syringe tool per liquid. Up to six syringe tools can be installed at once.

CONTROL IMPLEMENTATION

Jubilee's motion control is implemented by the *Duet* Ethernet Controller with the *Duex5* expansion board [8]. The Duet exposes a minimal web interface over a wired Ethernet connection that wraps high-level G-code commands into virtual buttons. It also provides a *macro*-writing feature that enables the user to write and execute small scripts stored locally on the board. We leverage this macro feature to encapsulate the complexity of operations such as tool changes. To reproduce our platform's firmware configuration, an outside user needs to only download these files from our Github repository and upload them to their Duet board's SD card.

After a user installs a new tool on the machine frame, they must add the tool to the software configuration. To achieve this, they upload the tool's parking location and offset to the configuration file on the SD card of the motion controller. After installation, switching from an old tool to a new tool is handled automatically by the default controller firmware; the user can invoke a tool change with a single G-Code command specifying the tool they wish to pick up. I.e. the command "T1" would first park the current tool, if one is currently loaded, and then pick up the tool with index 1. Following this command, the command "T0" would park tool 1 and then pick up tool 0.

We generated machine instructions for each use case in the G-code numerical control language. We used an off-the-shelf slicer for 3D printing, Simplify3D, for generation of (multi-head) 3D printing instructions. A custom JavaScript interface for converting SVG vector images to G-code was used for tasks that required an input path. Custom Python scripts were used to generate G-code directly in the event that a path was not needed. Each generated G-code file was sent to the machine through the Duet ethernet interface.

DOCUMENTATION

Using, fabricating, and extending Jubilee is documented in an online repository https://github.com/machineagency/jubilee. The documentation is an integral part of the contribution, as we intend for users to be able to make their own machines with only the materials listed in the repository. Therefore, we have extensively documented the assembly process and linked it to a detailed bill of materials (BOM). All parts and their vendors are itemized in the BOM. For the three components that must be machined, we provide links (included in the BOM) to vendors who will affordably produce or supply these parts in single unit quantities.

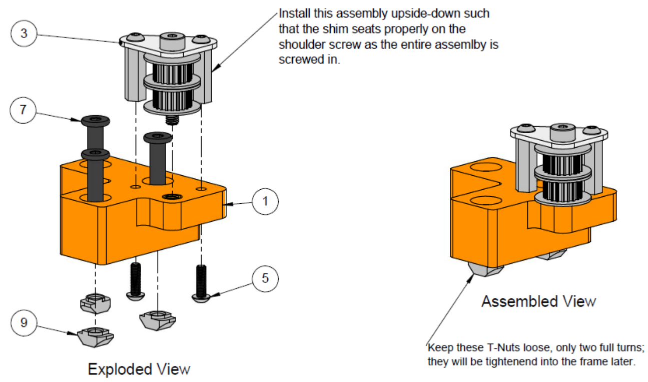

Figure 9. An example step as illustrated in our online assembly documentation. The legend with part numbers is not shown.

The assembly instructions are presented in a visually rich step-by-step fashion enabling non-experts to simply follow the steps to build their own Jubilee. Items are called out by type, and assemblies are presented in both exploded and assembled views. To minimize errors during assembly, we designed most parts to only fit together in one orientation.

Furthermore, we supplement sections of the instructions with 3D-printable fixtures. These fixtures hold some subassemblies in a particular orientation while the assembler installs other parts. While the instructions answer the question of location or "what goes where", these fixtures are intended to answer the question of process, or how one might physically put the components together. As most mechanical fasteners do not simply "snap" together in a manner akin to LEGOs, we supplement the assembly instructions with fixtures with the intent of helping new machine builders understand the various processes necessary to join components together.

Jubilee Component Cost Breakdown

Component	*Price*
Toolchanger Locking System	\$120
Motion System	\$1100
Aluminum Bed Plate	\$80
Electronic Control Boards	\$260
Dual Extruder Tools	\$400
Grand Total	\$1960

USE CASES

We illustrate four use cases that demonstrate possible applications of the Jubilee platform. Individual specialized machines do exist for each use case; for example, a dual-extruder 3D printer can handle multi-color 3D printing, and a liquid-handling machine can handle automated pipetting tasks. However, with Jubilee, rather than needing different machines for different tasks, one simply swaps out the tools. A user is not locked into pre-existing functionality; they are free to mix and match tools to explore different fabrication workflows. While we mention four examples below, there are many more potential applications as Jubilee's platform allows and encourages users to develop their own tools.

Multi-Pen Plotting

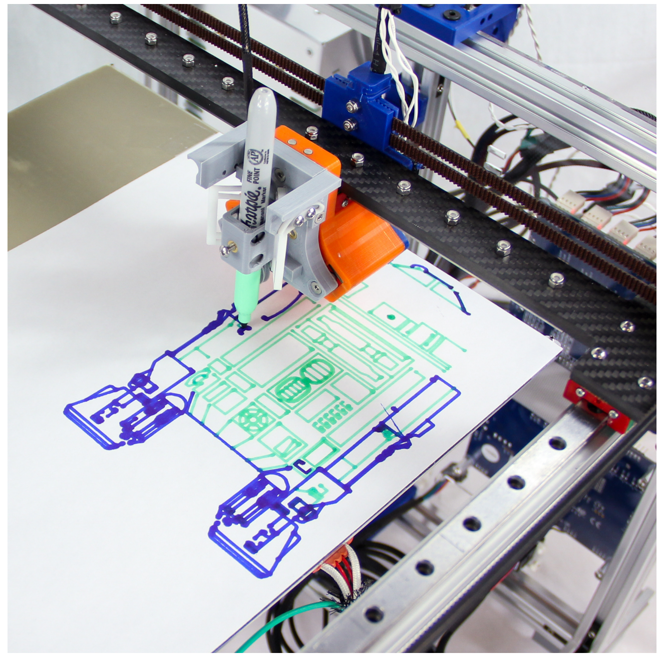

Figure 10. An image plotted with two different pens. The pen is actuated with a cable which pulls it off the paper.

Desktop plotting machines, also known as "plotters", are popular among hobbyists for their affordability and low barrier of entry to the world of desktop machines. There are a variety of commercial plotters available, such as the Silhouette Cameo and the AxiDraw. These machines vary widely in feature set, but are in essence two-axis machines that can move a drawing or cutting implement across a 2D surface. Online communities have formed around the exploration of these machines' capabilities, where people share plotted pieces, machine designs, and code for generative designs. These enthusiasts can be found tweeting with the *#plottertwitter* hashtag, but they have also formed private Discord server to aid in the sourcing of plotter-relevant resources.

Plotting is a simple demonstration of Jubilee's multi-tool capability, where it picks up a series of pens and uses them to draw a multicolor image. Figure 10 shows an example vector drawing of R2-D2, plotted in blue and green. For this example, we extracted two sets of paths from a vector graphics file, and designated one set of paths to be drawn in blue and one in green.

Multi-Head 3D printing

Some desktop fused filament fabrication 3D printers offer the ability to print with multiple materials. Doing so enables models to be printed with multiple colors, from mixed material types (flexible and rigid), and with shapes uninhibited by the force of gravity using printed dissolvable support structures.

Various implementations of multi-material printing already exist. The MakerBot Replicator 2X and Ultimaker 3 are two commercial examples of multi-material 3D printers with dual extruder carriages [24, 44]. Here each extruder is dedicated to a filament type. However, in these cases, both extruders are attached to the same moving carriage, and the idle extruder is subject to "drool" excess filament on the part. Furthermore, only two filaments may be used at any given time. Another approach to multi-material 3D printing is to change not extruders but filaments through a retraction process as with the Prusa Mk3 MMU2S system [36]. However, this process is significantly slower than a multi-extruder implementation. Finally, E3D, a 3D printer original equipment manufacturer (OEM), now offers a platform that enables true extruder-based tool-changing [22]; however, these systems are not sold as fully-assembled printers.

Figure 11. Left: A multi-color 3D print. Right: in-progress printing, showing both the partially completed print and the priming tower.

Jubilee can 3D print multi-material parts using an extruder-based tool-changing setup where color changes in the model correspond to tool changes for every layer. In Figure 11, we show both an in-progress shot of Jubilee printing a dual color model and the result. We also show the priming tower,

Gigapan Microscopy

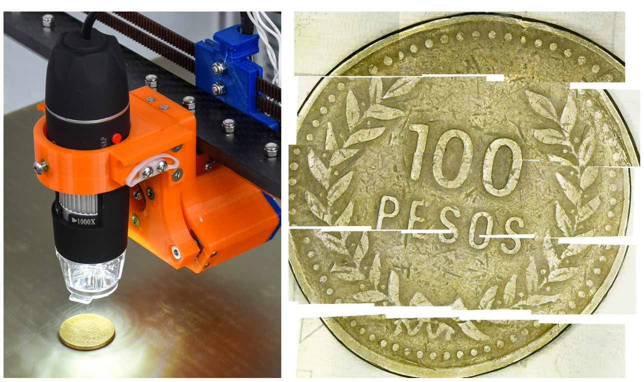

Figure 12. Jubilee can pick up a USB microscope to inspect the contents of the bed. This capability can include inspecting unfinished processes, such as partially-completed 3D prints and live cell cultures. In this case, the head is shown inspecting a coin. On the right, a hand-stitched image of the coin.

Gigapan microscopy is a method of high-resolution imaging that involves taking a series of microscope images across a 2-dimensional area. The images are then stitched together to form a large continuous image, useful for imaging techniques that require high-resolution input. In order to properly stitch the images, they must be captured at precise locations. This precision is achievable through Jubilee's CNC motion platform. Figure 12 shows the microscope-holding tool that we designed and used to capture a series of images.

Liquid Handling

Liquid handling is a common task in biology or chemistry laboratories. Although machines do exist to automate this process, it is often carried out by hand. Here, we present two example applications of our liquid handling tool. In the first, we use a syringe to dispense a controlled amount of liquid in a gradient across a 96 microwell plate as seen in Figure 13.

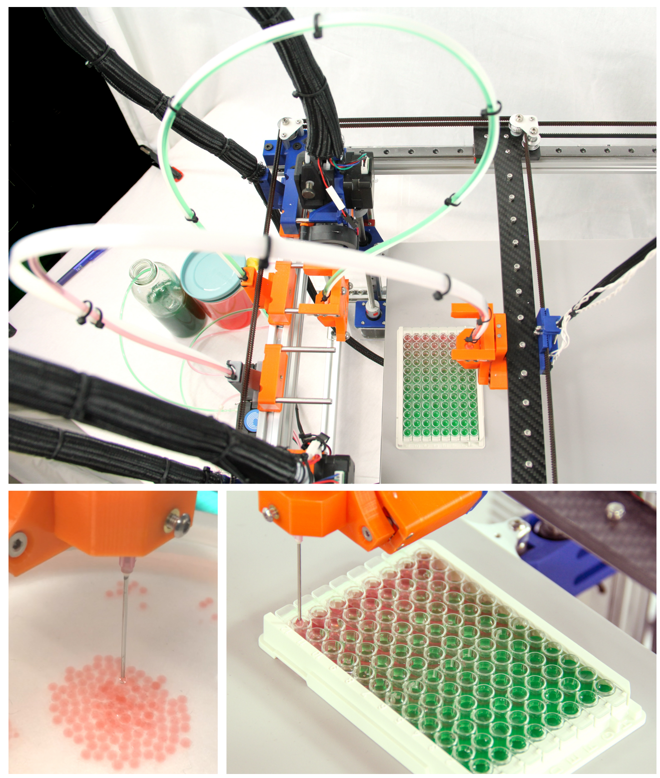

Figure 13. Here Jubilee is using two syringe heads to pipette different liquids. On the top, you can see the syringe tubing connecting to the liquid reservoirs. Bottom left, a spherification process. Bottom right, a gradient pipetted into a 96-well plate.

For our second liquid handling example, we take advantage of liquid spherification to create images formed from gelled spheres. Spherification is a chemical process often used in molecular gastronomy to create bursting "caviar" spheres of various liquids. In this example, sodium alginate is blended with a flavorful liquid and dripped into a solution of calcium lactate. The outside of the bead of alginate solution gels on contact with the calcium bath, creating a sphere that holds its shape even when removed from the bath. We can control the extrusion of alginate solution to create 'caviar' of different sizes. Shown on the bottom left of Figure 13.

LIMITATIONS AND FUTURE WORK

Both Jubilee's frame and work envelope are currently fixed in size, which limits the total number of parked tools to around five total. In the future, we would like to provide a parametric design of Jubilee such that users can change the work envelope to accommodate more tools or bigger work pieces.

The mechanical implementation of Jubilee uses timing belts, enabling rapid motion of the tool. This is ideal for high-speed low-force applications such as 3D printing. However, the trade off is that we cannot exert high forces with timing belts, making high force applications such as milling metal infeasible. Future work could include exploring other motion platform implementations for high-force applications.

While adding a tool to Jubilee has been streamlined in hardware, controlling new tools in software sometimes requires the user to write custom code. While many software solutions exist for 3D printing, plotting, and milling, they are difficult to modify for applications outside of their intended use. While Jubilee is compatible with many existing computer aided manufacturing (CAM) packages, specific settings must be adjusted before they can be executed. We have provided example code in our documentation. We plan to explore general purpose software control for custom applications outside of traditional machining in future work.

While Jubilee can used for a variety of custom multitool applications, neither the G-code language nor the firmware controller supports a means for real-time sensor feedback or closed-loop control. Consequently, users cannot extend Jubilee with tools that would necessitate real-time response to sensor input. However, sensor feedback and closed-loop control can be implemented at a higher level by encapsulating G-Code commands sent.

Upon releasing the design files and documentation for Jubilee, we have confirmed that several independent parties have begun building their own Jubilee machines. We estimate 8-12 hours to assemble a machine, not including time to print the parts. However, we have not yet formally evaluated the difficulties non-experts may encounter during the assembly process. We would like to specifically test the fabricatability of our design through reproduction by various user groups.

Zooming out from future implementation modifications we intend to tackle, we invite other researchers use Jubilee as infrastructure for their own automation applications. Jubilee is intended to scaffold the exploration of novel interactions. Jubilee's exact constraint design and automated tool lock ensures that even across thousands of tool changes, the user will not have to re-home or re-calibrate the machine.

For example, one could combine sensing and actuating heads in a single workflow. A researcher could 3D print a single layer, then use a probe tool to verify that the layer is fully fused with no gaps, then continue with the next layer and its layer verification. On existing hardware such a workflow would require hundreds of manual tool changes and become intractable. This allows us to explore questions in fabrication such as verification, safe operation, and run-time error handling.

Jubilee's kinematically coupled removable bed plate allows a user to remove the bed mid-workflow and later replace it without having to re-home the machine. This could enable novel workflows as well. For example, a researcher could place the bed plate in an oven to sinter partially-printed parts, or submerge the bed in a liquid bath to coat parts, or conduct any number of other operations, then return the bed plate to the machine for next steps. Furthermore, as the bed plates are interchangeable, they can be transferred from one machine to another. This transfer enables the exploration of workflows that leverage multiple machines or multiple users.

As HCI continues exploring the future of digital fabrication, especially with respect to the broadening of the user base towards personal fabrication and automation, we believe these kinds of explorations into novel interactions and workflows will form crucial future work.

CONCLUSION

In this paper, we presented Jubilee, an extensible machine for multi-tool fabrication. This machine is motivated by HCI research in materials and multi-tool processes, and a lack of tools and equipment for that research. We contribute an open-source hardware design of a tool changer, a motion platform, and several canonical tools including for 3D printing and liquid handling. We leverage principles of mechanical design to ensure high repeatability of tool changes. These designs are made to be extensible, so that a user can create application-specific workflows. We demonstrated the use of our machine through four example use cases that show the potential of multi-tool fabrication workflows to provide precise motion control for tasks currently too complex for most desktop fabrication machines. Ultimately, our goal is to provide much-needed infrastructure to allow practitioners and researchers alike to experiment with multi-tool fabrication, and to expand the scope of tasks that digital fabrication machines can handle.

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