Popfab: A Case for Portable Digital Fabrication

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ABSTRACT
We present a case study of Popfab, a portable multi-purpose digital fabrication tool. It is uses interchangeable heads (3D printer, CNC mill, and CNC knife) on a general-purpose motion platform that folds into a briefcase. Popfab contributed to the discussion of the future of digital fabrication tools by demonstrating the feasibility of both portability and both additive and subtractive manufacturing on a single platform. Portability is not yet a widely considered option for digital fabrication tools, but with Popfab we demonstrate that general site-specific personal fabrication is possible.

ACM Classification Keywords
J.6.b Computer-aided manufacturing (CAM): Computer-Aided Engineering; H.5.2.j Prototyping: User Interfaces; H.5.2.o User-centered Design: User Interfaces

Author Keywords
Digital fabrication; Machine Building; CNC; CAD/CAM; Portability; Prototyping; 3D printing

INTRODUCTION
Digital fabrication tools are increasingly of interest to interaction researchers [4]. Digital fabrication enables the production of unique parts with changes only in digital instructions. Therefore, the learning curve for digital fabrication is more similar to that of a computer program than the mastering of a manual skill, improving the accessibility of precision fabrication.

However, most digital fabrication tools are made either as large machine-shop tools or tabletop devices. To fabricate things with these machines users therefore have to travel to where the machine is. Computers also used to be large—even room-sized. But introducing portability to computer designs in the form of desktop computers, laptops, and later smartphones has allowed computation to be employed in many diverse contexts for many unanticipated applications. Can portability make a similar difference in digital fabrication?

Portability in digital fabrication tools could allow for site-specific fabrication using local materials. Jacobs and Zoran for example transported digital fabrication tools to collaborate with traditional ostrich eggshell jewelry craft in a hunter-gatherer community [1], introducing a new hybrid practice. Quitmeyer and Perner-Wilson developed a fully wearable studio practice for digital crafting in harsh hike-to environments, but the studio does not yet include digital fabrication tools [8]. As fab-in-the-wild efforts increase, portable tools become more relevant.

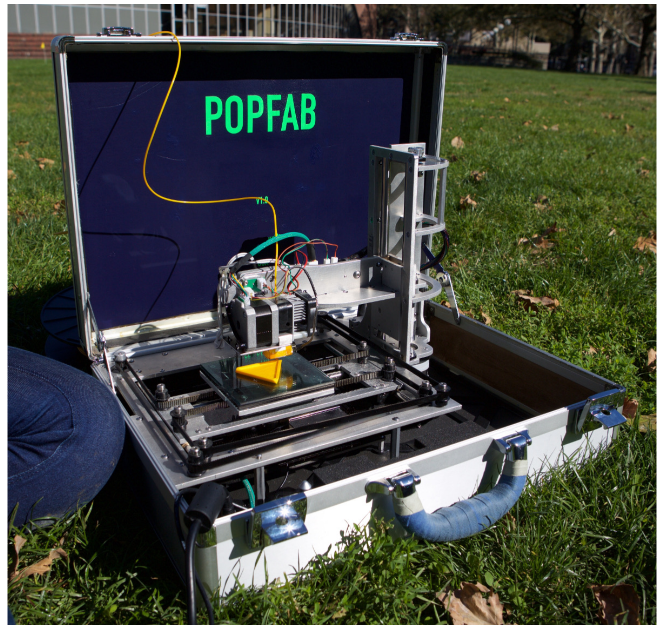

Figure 1. Popfab, a portable multi-purpose digital fabrication tool. Here it is configured with a 3D printing head for fused deposition modelling.

Portability could also introduce more flexibility in use of space. If a school for example did not have a room to allocate to a makerspace, portable digital fabrication tools could provide the functionality of makerspace tools without dedicated space. Portable tools could also be used in temporary locations, such as outdoors when weather permits, or at events such as hackathons, or as part of disaster relief efforts.

To explore the possibilities of portability in digital fabrication, we produced a portable and multi-purpose digital fabrication machine tool, Popfab, shown printing outdoors in Figure 1. Popfab provides a functional demonstration of portable additive and subtractive fabrication.

TEI '17, March 20 - 23, 2017, Yokohama, Japan

ISBN 978-1-4503-4676-4/17/03...$15.00
DOI: http://dx.doi.org/10.1145/3024969.3025009

RELATED WORK

Hand tools such as a drill, router, jigsaw, or belt sander are categorically portable. However, they lack the precision of computer numerical control (CNC), and require mastery of craft in their use. Schoop et al. augment hand tools with user feedback [10], but the user still must operate the tool and could make mistakes. CNC tools introduce autonomous precision, but also a work-envelope. The bed size of these tools becomes a crucial specification—it determines the size of the parts that can be fabricated.

The Shopbot Tools *Handibot* gets around the work envelope limitation by having end mill stick out of the machine tool [13]. The *Handibot* can be placed on any surface to mill into it. The *FreeD* and the *Shaper Origin* both avoid work envelope limitations by pairing local computer-controlled precision with less precise, global, hand-held motion [18, 9]. These examples are all subtractive machine tools, whereas Popfab also has other heads, including additive.

Weichel et al. and Teibrich et al. demonstrate milling and 3d printer combination machines [16, 12], but their machines do not easily accommodate other end effectors.

Site-specific production also includes measurement and design phases. Weichel et al. demonstrate tools that make the transfer of dimensions more fluid [15]. Lau et al. demonstrate a tool that helps users design context-specifically [2]. Willis et al. demonstrate a series of fabrication tools which use real-time input as their designs [17]. Popfab is only portable at the fabrication stage, but does not address in-context or portable design.

WALK-THROUGH

We present Popfab, a portable, multi-purpose digital fabrication tool that fits in a briefcase. How might someone use this tool, and how does this differ from how digital fabrication tools are currently used?

Imagine being confronted with a problem for which a technical solution could be rapidly prototyped. As an example, imagine a simple part breaking for which a replacement could be 3D printed. Popfab has a 3D printing 'head', a milling head, and a spring-loaded holder that can fit a blade or pen. The user who wishes to 3D print a replacement part opens the Popfab briefcase and pops up the z-axis, fixing it into its popped-up position with two thumbscrews. The user selects the 3D printing head and attaches it to the z-axis via its kinematic mount. The mount is preloaded with another single thumbscrew. The machine is powered through wall power and controlled through USB. The user connects the machine to a laptop and starts the machine's control software. After zeroing the 3D printing head on machine's bed[1], Popfab is ready to used as a regular 3D printer. The pop-up and zeroing procedure takes a few minutes.

Imagine if instead a user would like to rapidly prototype a circuit board. Popfab's Z-axis is popped up in a similar fashion,

[1]The zeroing operation is the same for all heads and entails the user moving the head down until it is physically touching the bed, and marking this as the zero position. This process is the same for commercial (non-portable) CNC tools.

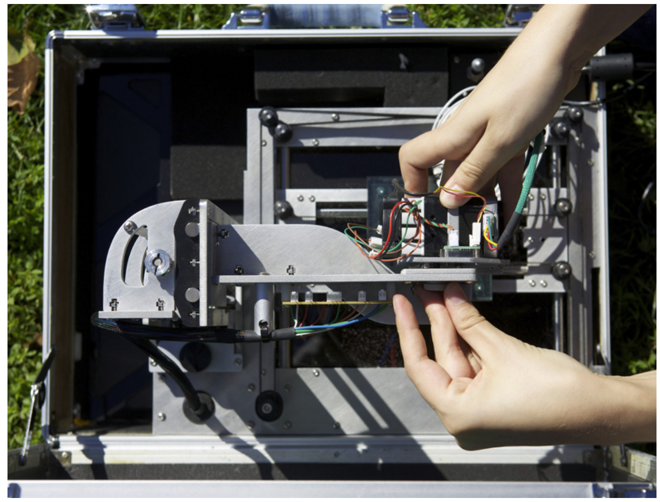

Figure 2. The different Popfab end effectors (or 'heads') are attached after the machine is popped up. Without a head attached the z-axis can fold down into the rest of the suitcase.

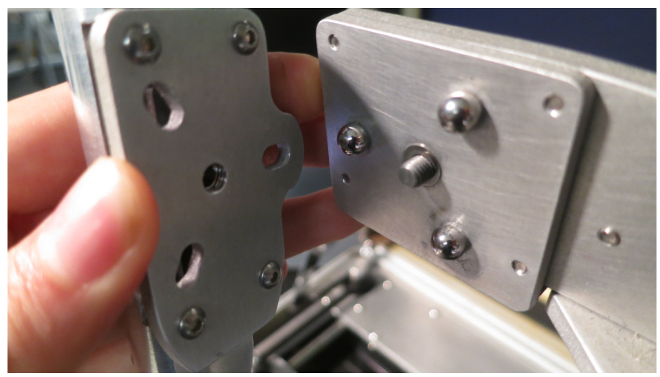

Figure 3. A three-groove kinematic coupling allows for repeatable repositioning of the heads with a single thumbscrew for preload.

but now the user instead selects the milling head, attaching it through the kinematic mount. After zeroing the head Popfab is ready to be used as a milling machine subtractively removing copper from a circuit board blank.

IMPLEMENTATION

The mechanical architecture of Popfab represents a compromise aimed at optimizing both support for multiple fabrication methods and ease of setup, under the constraint of portability. The portability of Popfab is mostly achieved by folding the machine, but also by reducing the available work envelope. The first Popfab machine was made in 2012, at the time its work envelope was not dissimilar to popular consumer 3D printers or mini-mills with a work volume of $10\times10\times20$ cm.

Our approach is a XY stage built into the base of a briefcase, with a folding Z axis supporting a cantilevered arm on which the toolhead is mounted. This configuration minimizes the complexity of the folding mechanism by limiting it to one axis. We anticipated that attempting to cantilever a two-axis stage as stiffly and repeatably would be significantly more

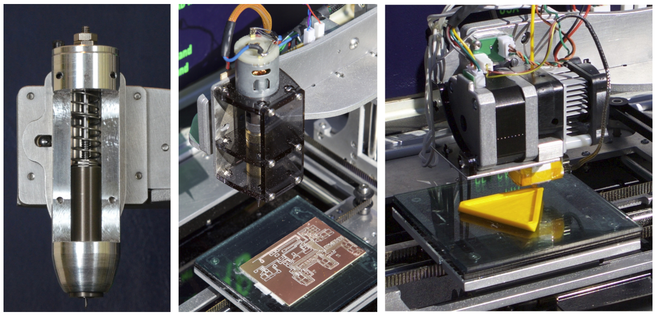

Figure 4. A swivel knife head, a spindle head, and an FDM 3D printing head.

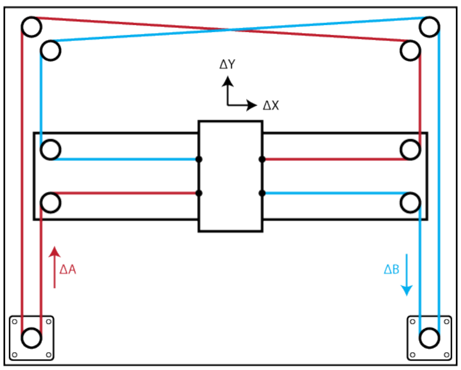

Figure 5. CoreXY reference mechanism used with permission from [5]. To move the center stage in X and Y, the motors move the belts in directions A (red) and B (blue). The equations of motion are $\Delta X = \frac{1}{2}(\Delta A + \Delta B)$, $\Delta Y = \frac{1}{2}(\Delta A - \Delta B)$, $\Delta A = \Delta X + \Delta Y$, $\Delta B = \Delta X - \Delta Y$.

difficult. Furthermore, setting up a two-axis folding stage would add to the users' setup time and introduce opportunities for inconsistent mechanical alignment after each setup.

For the XY stage we chose to use a parallel kinematic stage so that we could avoid the extra moving mass required when stacking the X stage on top of the Y serially [14]. Specifically, we chose *CoreXY* [5], a variation on H-bot kinematics with and additional crossing of the timing belt (see Figure 5). CoreXY offers high spatial efficiency (the ratio of work envelope to mechanism envelope), low inertia (well suited to 3D printing), and sufficient stiffness for low-force machining.

With this overall architecture the folded Z tower nests into the XY stage (see Figures 2 and 6), and the build surface is moving rather than the head. Most 3D printers avoid moving the print in XY because it can cause tall prints to shake under their own mass during rapid accelerations, and also because the inertia of the moving stage changes throughout the print. However, we decided this trade-off was acceptable because the limited height travel on the machine precludes printing very tall parts, and this is not a concern when milling. CoreXY uses a timing belt for XY, which is good for high-speed motion in 3D printing, but not as good for high-force applications such as milling metal. Because our spindle is intended for milling circuit boards, it does not encounter cutting forces high enough to make this a concern.

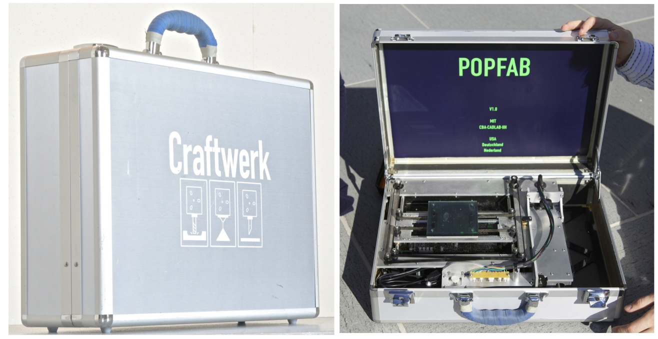

Figure 6. Popfab's z-axis folds down to fit into a briefcase.

Toolheads are easily interchangeable due to the use of a ball-and-groove kinematic mount (see Figure 3 for the coupling and Figure 4 for the different tool heads). These interfaces are typically found in precision machine design because of their extremely good positioning repeatability [11]. For Popfab though their key attribute is high stiffness with a single source of preload—in our case provided by an easy-to-use thumb knob. This makes changing toolheads simple and tool-less. New toolheads can easily be added.

For Popfab, we have created a 3D print head, a spindle head, a swivel knife head, and a plotter head. We also have an experimental microscope head (for gigapan), and a pipetting head. Creating heads requires the 3-groove pattern for mounting, and integration into the electronics and controls.

For the control electronics and power, we used an off-the-shelf 3D printer board *Printrboard Rev C* from Printrbot with 4 stepper motor controllers, running *Marlin* firmware to interpret G-code, and a 200W power supply [6, 3]. For streaming the G-code from the control computer, we used *Pronterface* [7]. At the time of design, this combination was an affordable off-the-shelf solution for G-code running 3D printers. For our specific implementation, we contributed parallel kinematics code to the open-source Marlin codebase. However, this electronics and software combination was limited in its usability for different processes such as milling, gigapan, or pipetting. We for example used the same controller component for the spindle motor as for the heating element of the 3d print head. Issues that arose with this approach are further discussed in the limitations section.

Alongside the briefcase machine, we have a auxiliary case that contains the heads, power supply, end mills, and knives. We attempted to make Popfab as self-contained as possible, but decided on an accessories bag for weight distribution and ease of carrying. We also used the auxiliary case to store some materials including vinyl, copper-clad boards, and PLA filament, as well as a portable soldering iron and a supply of surface-mount electronic components.

USAGE

Popfab is meant to be a portable alternative to a digital fabrication workshop such as a makerspace. As far as we know, Popfab is the only 3D printer that can qualify as a 'personal item such as a laptop or briefcase' for airplane carry-on, and it also happens to be a milling machine. It has traveled to 3 different continents as carry on luggage[2]. Its small form factor and high production value have made it well suited for exhibitions and demonstrations, and it has spent much time working as a demonstration of digital fabrication. We have also used Popfab to mill circuit boards for last-minute demos while travelling, or to 3D print hooks we thought could be useful in the cafe we were in. However, we only had one Popfab, and most of its usage remains anecdotal.

Limitations

The size of objects produced with Popfab is limited by what material can be placed into the machine's work envelope. Popfab can be used to fabricate on-site, but can only make things smaller than itself.

Popfab is not battery powered, which limits its portability. Popfab runs on 12-24V DC, and we estimate Popfab could use up to 80W during operation, making it possible to run on e.g. a car battery. However, with a redesign of the electronics for low-power, these numbers could be significantly improved.

A less obvious limitation stems from multi-head control. Making new heads for Popfab such as a laser diode for laser cutting is mechanically trivial. However, for the electronics and control software we used tools originally designed for 3D printers. The hardware expected a certain flavor of G-code that could be generated by some .stl slicers typical of 3D printing, but not e.g. by off-the-shelf toolpath planners for CNC mills. We produced the appropriate G-codes for milling by writing custom post-processors for milling instructions, and wrote other custom G-code translators to be able to use e.g. the plunger on the pipetter. However this G-code hacking was a usability limitation that prevented other users from easily using Popfab for general fabrication besides 3D printing. A more flexible electronic control and software solution would be better for this kind of multi-process tool.

DISCUSSION

We developed Popfab to explore portability for digital fabrication—what is the laptop of digital fabrication and how is it useful? In practice, we predominantly used Popfab to demonstrate digital fabrication. But Popfab did served as as a discussion tool for what the future of digital fabrication could look like— a functioning machine (albeit with usability kinks) as a prop with which to imagine a future where people can carry personal digital fabrication tools around with them.

In the near future, there are clear wins for portability with digital fabrication such as site-specific or temporary location fabrication and flexible use of space (e.g. classroom). Portability entails ease of transport, but crucially also ease of set up. If these kinds of tools were to exist, digital fabrication could be employed more flexibly both in new places, but also at unusual times or on-the-go. Materials that might be difficult to remove from a site can still be used with digital fabrication tools if the tools are brought there.

[2]Surprisingly, although it has been on more than 20 flights, airport security only asked to open the Popfab briefcase once—for most airports apparently a pop-up digital fabrication machine does not look suspicious in X-ray at all.

One of the challenges of portability in digital fabrication is that today's digital fabrication tools are not entirely self-sufficient. A host of secondary hand tools and materials are necessary to produce finished objects. For Popfab, we started accumulating these accessories in an ever-growing side case. 3D printed parts for example need their support materials removed, CNC milled parts need their last attachment tabs to be filed off. Digital fabrication needing a context of tools dovetails into Quitmeyer and Perner-Wilson's portable studio practice. Another consideration is the availability of raw materials such as thermoplastic and UV cure resins for 3D printing, cardboard and polymers for laser cutting, copper-clad boards for PCB fabrication, etc. Portable and widely available digital fabrication machines would mean that demand for auxiliary tools and feedstock would go up. Perhaps this is a future where corner stores sell materials and tools instead of finished products.

In the long term, we hope that portable digital fabrication tools change not only how we currently use digital fabrication tools, but how people interact with objects and products more generally. Digital fabrication tools might become part of a point-of-sale at stores and markets, producing parts on demand. Where coffeeshops now offer wifi and electricity for laptop wielding patrons, perhaps later they will offer fabrication space and feedstock. Portable personal fabrication tools could greatly change how we currently deal with supply chains and inventory. We think that this has great opportunity for enabling a future where personal fabrication plays a more pervasive role in our lives.

CONCLUSION

We introduced Popfab, a multi-purpose machine tool. One of its key features is portability—it fits the functionality of a 3D printer, CNC mill, CNC knife, and other heads into a single briefcase by using a pop-up machine platform. Its portability enabled quick-start on-site digital fabrication. Popfab's portability did not come at the expense of its precision or utility as a machine tool. Popfab contributes to a discussion of the future of digital fabrication machines by demonstrating the feasibility of portability. It also demonstrates versatility by using multiple heads.

In the future, we hope that the benefits of portability (including site-specific fabrication and flexible workspace) are included in many more digital fabrication systems. We also hope that lessons learned about versatility and extensibility of these tools' control systems are incorporated into future implementations.

ACKNOWLEDGMENTS

The authors would like to thank Erik de Bruijn and others at Ultimaker, David Wallace of MIT Cadlab, and Neil Gershenfeld of the MIT Center for Bits and Atoms.

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