Mobile Fabrication

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ABSTRACT

We explore the future of fabrication, in particular the vision of mobile fabrication, which we define as "personal fabrication on the go". We explore this vision with two surveys, two simple hardware prototypes, matching custom apps that provide users with access to a solution database, custom fabrication processes we designed specifically for these devices, and a user study conducted in situ on metro trains. Our findings suggest that mobile fabrication is a compelling next direction for personal fabrication. From our experience with the prototypes we derive the hardware requirements to make mobile fabrication technically feasible.

Author keywords: fabrication; mobile computing.

ACM classification keywords

H.5.m. [Information interfaces and presentation]: Misc.

INTRODUCTION

Personal fabrication has emerged as a topic in human computer interaction [9]. 3D printers, initially considered tools for prototyping [20], are now explored as tools to help users solve engineering problems, such as the design and assembly of furniture and vehicles [27], optimization of objects' aerodynamics [35], or repair of objects [32].

While fabrication currently takes place in offices, labs, and workshops, the current evolution of 3D printing hardware suggests that 3D printers are about to achieve a mobile form factor (e.g. *iBoxNano* (iboxprinters.com) or *Olo* (*olo3d.com*)). Future users may soon have access to such devices while on the go. In an analogy to mobile computing, such mobile fabrication could provide users with access to fabrication anywhere anytime.

This raises a number of questions: what will users do with such devices while on the go? How will the hardware develop? What issues and limitations will users encounter? In this paper, we try to find answers to these questions by anticipating the evolution towards mobile fabrication.

We proceeded in three steps. First, we conducted a survey in which participants told us what they would fabricate with a mobile fabrication device. Second, we tested the practicality of making these things using a 3D printer which we retrofitted for mobility and drove using a mobile phone running a custom solution app (Figure 1a). Third, we created a "human-assisted" prototype that allowed not only for a mobile form factor, but also allowed us to overcome some of the limitations faced by actual 3D printers (Figure 1b). We use these insights to envision what future mobile fabrication devices might look like.

Our main contribution is the overall exploration of this future: each of the separate activities gives us a chance to sketch a more complete picture of what that future of mobile fabrication might be like.

Figure 1: According to our survey, one use case of mobile fabrication is to fix things that break while on the go. This user, for example, fabricates a hex key to fix his broken bike light using either (a) a custom "mobile" 3D printer or (b) a "human-assisted" 3D printer based on an extruder pen. We drive both using a mobile phone running our custom app.

RELATED WORK

Our work builds on the work of HCI researchers who explored how to help non-engineers fabricate. We also build on humans assisted fabrication.

Fabrication systems that provide domain knowledge

To help non-engineers engineer, researchers in HCI and graphics have developed tools that incorporate the required domain knowledge, such as interactive controls (*Maker's Marks* [7]), the dynamics of model airplanes (*Pteromys* [36]), the structural engineering of furniture (*SketchChair* [25]), or how to design enclosures (*Enclosed* [37]).

Design for fabrication on context

With mobile fabrication, users create objects that are part of and connect to their context of use. Several research projects have investigated how to allow users to design objects in their context. *Tactum*, for example, lets users design bracelets directly on the wearer's arm [8]. *CopyCAD* [6] brings physical objects virtually into the fabrication environment. *MixFab* [38] lets modeling and physical environ-

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ment blend together. More recently Koyama et al demonstrated how to generate geometry that connects 3D models to their context (*AutoConnect* [14]).

In this paper, we define the term "mobile fabrication" as fabrication on the go. We think of mobile fabrication as a first step towards what we would call pervasive fabrication, i.e., personal fabrication anywhere, anytime. The term pervasive fabrication was previously used in a workshop at UbiComp 2013 [16]—however there it was used to denote "fabrication for everyone".

How-to instruction repositories

We guide users in the fabrication process using how-to instructions. Several researchers studied the sharing [2] and evolution [21] of the communities surrounding such repositories. Recently, Torrey et al. [34] investigated searching for how-to instructions. The proposed instruction system builds on their findings by allowing users to filter by tool, providing a wide variety of keywords for every object, and by presenting instructions in a highly visual way. Two notable examples of commercial online repositories related to fabrication are *Thingiverse.com* and *Instructables.com.*

Helping users trace

In our second prototype (Figure 1b) we let users trace instructions on a phone. Tracing is a method, which allows users to use relatively imprecise input techniques, yet achieve precise output. T*he drawing assistant* by Iarussi et al. [12] helps users trace photographs and subsequently fills in details. Also *PortraitSketch* [40] allows users to trace images, albeit more specifically geared towards sketching human portraits. Researchers have used projectors to bring tracing to the physical world. *Projector guided painting* [5], for example, lets users trace projected art on a canvas. *Sculpting by numbers* [24] projects guidance on how to improve physical models. *LightGuide* [31] projects directly on users' hands, instructing them what to do.

Human-assisted fabrication

Several research projects have explored the concept of human fabrication guided by a computer system. Some advantages include large flexibility and fast fabrication without large actuation hardware. *Haptic Intelligentsia* [17], for example, guides users along a path using a Phantom force feedback device fitted with a glue gun, resulting in simple 3D objects, such as cylinders.

In "*the wise chisel*," Zoran et al. [43] provide a great overview of handheld fabrication tools extended with guidance mechanisms. *Free-D* [42] elaborates on the concept of guidance by deactivating the tool when off-bounds. Similarly, *Augmented Airbrush for Computer Aided Painting* [29] applies this idea to airbrushes. *D-coil* [22] lets users fabricate 3D models out of wax.

While the systems above track users, Devendorf's *being the machine* [4] uses a form of human-assisted fabrication that does not require tracking. The system uses a laser pointer to point users to where to apply material, with the goal to make the fabrication process more expressive through human input and the resulting reduced precision.

The term *human-assisted manufacturing* was coined by Yoshida et al.; their system guides users through the fabrication of large objects by piling chopsticks using a chopstick blower [41].

TWO SURVEYS: THINGS TO MAKE ON THE GO

We conducted two surveys with the primary objective to create a basis for our subsequent work. The objective of the first survey was to create a list of objects potential future users might want to fabricate while on the go. The objective of the second survey was to prioritize this list. The resulting prioritized list of objects became the basis for our subsequent engineering.

Survey one: scenarios worth solving with fabrication

We recruited 40 volunteers from our institution (age 18-38, 12 female). Each participant filled in a questionnaire with the following wording "We are studying 3D printing, specifically a potential future where people might carry a tiny 3D printer with them at all times, as we do with mobile phone. We are wondering about potential use cases. Please list five on-the-go scenarios where being able to make a missing object quasi-instantaneously would really help you out."

Results: Each participant listed on average of 3.9 objects for a total of 75 distinct objects. The list contained 50 objects that could be produced by a mobile 3D printer.

The majority of objects could be classified into the following use cases: *fixing/replacing (9 objects):* shoelace, shirt button, hex key, cable tie, carabiner, tripod for fixing/soldering things, replacement parts, screw anchor, and hook to grab inaccessible things. *Forgotten/lost (19 objects):* key, earring retainer, cutlery, mugs/cups, shopping cart clip, bottle plug, phone case, phone stand, LEGO, dog bowl, ball, plectrum, earring, padlock, laptop stabilizer, signs, bookmark, pen holder, and Tupperware. *Medical (7 objects):* bandages, earplugs, toothpick, hair clip, hair brush, toothbrush, and rescuing tools. *Social (9 objects):* tactile renditions for blind people, game/chess pieces, personal presents, dice, name tags, figurines, scale models for communication, (wedding) rings, artistic objects, and business models. *Outdoors (6 objects):* carabiner, tent stake, ice scraper, survival knife, spikes for shoes, safety equipment. Objects outside the scope of mobile 3D printing (as of now) included food and medication (because the necessary substances would not be available) and umbrellas & clothes such as sun hats (because they would be too large to make).

Discussion The useful scenarios in which objects on the list would be required could be characterized by three main qualities: (1) *Unexpectedness:* users are unlikely to incidentally carry the required objects. (2) *Importance:* not having the object costs time, money, safety, or reputation. (3) *Urgency:* The problem requires a timely solution—otherwise users would solve the problem later, by buying the object or by fabricating it at home or at work.

To help us focus our subsequent engineering effort on the most relevant objects, we conducted a second survey in which we prioritized objects on this list.

Survey two: prioritizing the scenarios

We recruited a separate set of 39 participants (age 20-45, 18 female). Each participant rated each of 12 use cases of mobile fabrication. We had created the list by sampling each of the 5 categories from the first survey and then making the list of objects more tractable by adding a brief description of a context of use. Participants rated objects in the resulting scenarios as “must have”, “nice to have”, and “uninteresting”.

Results: The three scenarios that received the highest number of “must have” ratings were: (15) “make a key when you locked yourself out at home”, (11) “create earplugs when there is somebody snoring next to you in a long distance bus”, and (9) “make a carabiner to fix a bag strap on the way to plane.”

Scenarios with the highest combined number of “must have” and “nice to have” ratings were: (38) “Make an Allen wrench to fix a bike lamp” (36) “Replacing shoelaces when they break during a longer hike”, and (36) the carabiner mentioned before. The least popular scenarios (with largest number of “unimportant” ratings) were: (25) “replace a lost earring retainer”, (11) “make a shopping cart clip”, and (8) “make disposable cutlery”.

Qualitative feedback: Overall, participants’ responses to the concept of mobile fabrication was positive, while some people saw it mostly as a cool gadget, most said they would use it to solve actual problems. A typical question that was raised was the weight of the printer. One participant commented on this in the context of the hiking scenario: “[the printer] also needs to be carried and on a hike you usually try to minimize weight. However, the ability to make things as needed may reduce what I need to carry in terms of emergency backup equipment.” Three others came to similar conclusions.

Twelve participants uttered security concerns with the *key* scenario. In particular, they were worried about someone compromising the system, downloading the key, and breaking into their homes. These are relevant concerns and very much in line with security concerns resulting from digitalization as a whole [32].

Finally, one of the participants pointed out the need for engineering: “Do people even have the creativity to think of the objects they need to print to solve the respective issue at hand?” This raises an excellent point and became the basis for many subsequent design decisions, in particular the decision to create a solution database that we would provide to users together with the fabrication hardware.

Discussion The second survey provided us with a ranking of objects that helped us focus our subsequent engineering effort. Furthermore, the survey had raised the question about engineering issues, which we decided to address using a solutions database. Finally, the large number of “must have” ratings in the second survey suggests that mobile fabrication has the potential to matter.

A limitation of the study is that it focused participants on utilitarian scenarios (see also [28]). Follow-up work may want to include non-utilitarian scenarios, such as mobile fabrication for purpose of entertainment or to allow users to explore an idea that occurs to them while on the go.

ENGINEERING & PRACTICALITY CHECK 1: 3D PRINTER

Building on the results of our surveys, we set out to test the practicality of mobile fabrication. We started by creating the first iteration of what a mobile 3D printer might look like, wrote a matching app for it, and then tried to fabricate the list of desired objects from our survey. To satisfy the urgency objective, we re-engineered all objects so as to minimize build time. Our overall objective was to investigate what objects this type of device would be able to produce and where mobile 3D printers would fail in order to derive implications about mobile 3D printer hardware.

A first iteration on mobile fabrication hardware

We modified an off-the-shelf 3D printer to allow for mobile use (Figure 2). We chose our hardware components so as to allow for one hour of printing time, which would allow us to fabricate one larger or three smaller objects.

We started out with a 3D printer (M3D printm3d.com) that extrudes liquefied (PLA) plastic (aka *fused deposition modeling* or FDM). We wanted to use the printer truly “on the go” and FDM worked well here because it continues to print when held sideways or even upside down and while being shaken. This criterion prevented us from using certain other printer designs, including those based on stereolithography as they use a container of liquid resin that needs to be upright and stationary while printing (e.g. *Olo*).

In order to optimize the form factor, we reduced the height of the device as shown in Figure 2. We achieved this by removing a 10cm slice from the middle section of the casing and shortening the internal mechanics accordingly. This reduced the printable height from 11.6cm to 2.2cm, and the print area to 9.1x8.4cm. This was acceptable, because objects that print within 1h rarely exceed this volume. The resulting printer weighted 1190g and measured 9 x 18.5 x 18.5cm, which makes its size comparable to a handbag or smaller messenger bag. We added a shoulder strap, allowing users to wear the printer like a messenger bag, as shown in Figure 1a and Figure 2.

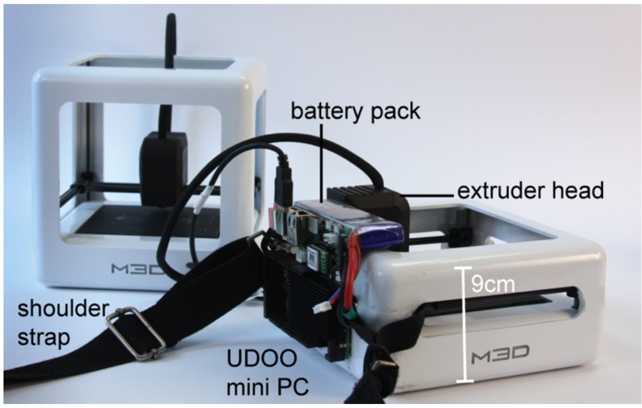

Figure 2: The modified printer, a *Micro 3D* printer reduced in height and extended with battery pack and UDOO miniPC.

To allow the printer to work on the go, we retrofitted it with a battery pack that allowed for about one hour of printing time (1800mAh). We attached a single-board computer (*UDOO Quad* board) running a web-based host (*OctoPrint* [13]) on top of Linux (*Udoobuntu* 1.1). This allowed us to control the printer through a phone app connecting to the *OctoPrint* server as a web app.

To allow users to look up engineered solutions, we wrote the app shown in Figure 3. The app allowed users to search for solutions for the on-the-go scenarios from the survey and it returned hand-engineered annotated 3D models. The app ran in a web browser and was written in *AngularJS*. The app retrieved the 3D models from a cloud service (*Firebase*), which used a NoSQL database to store relevant data in JSON format. We stored the images accompanying the 3D models with an image service provider (*Cloudinary*). The app interfaced with *Firebase* and the server using HTTP requests.

Walkthrough

Users operated the system as illustrated by Figure 3. Here a user uses the system to re-attach a bike lamp. (a) He wants to ride home in the dark when he discovers that the lamp sags—the mount of the bike lamp is broken. In order to make his ride home safe, he decides to re-attach the lamp. (b) Close inspection reveals a loose hex nut, but our user does not carry the matching hex key. (c) He starts our app and enters “hex key”. (d) The system offers several models of hex keys—all custom designs reduced to the bare minimum to allow for fast fabrication. The first two are sized 5mm and 6mm, but the user is uncertain about the diameter of the nut. He therefore picks the third model, which offers two heads: one for 5mm and one for 6mm.

(e) The user produces the hex key, which takes 25 minutes. The printer works in any orientation and while moving. Since the app works while running in the background, the user is free to roam around and to use the phone in the meantime. (f) 25 minutes later the app plays a notification sound. The user removes the hex key from the print chamber, (g) re-attaches the lamp by tightening the hex nut, and (h) rides on safely.

Designing for mobile fabrication based on 3D printer

In order to engineer the solutions in the database, we got together with a team of three lab members and recreated the 3D printable designs from the study list for our mobile 3D printer setup. We generally started with objects from an online repository (*Thingiverse.com*) and then optimized for use with our mobile printer. Most designs only required optimizing material use in order to maximize printing speed. We created five types of optimizations, which we discuss at the example of the aforementioned hex key (Figure 4 shows 5 close-ups).

(a) Use strong geometric structures. The handle of the hex key has to be strong enough to transmit large amounts of torque, yet we still want it to print quickly. As shown in Figure 4, we address this by creating a handle in the form of a flat structure of connected beams (aka truss) optimized to handle torque.

(b) Avoid support material by designing in 2½D. To prevent buckling, we need to add several very narrow extra layers on top for a L-shaped cross section, but we add them on one side resulting in a 2½D design that prints is flat against the build platform and does not require support-material.

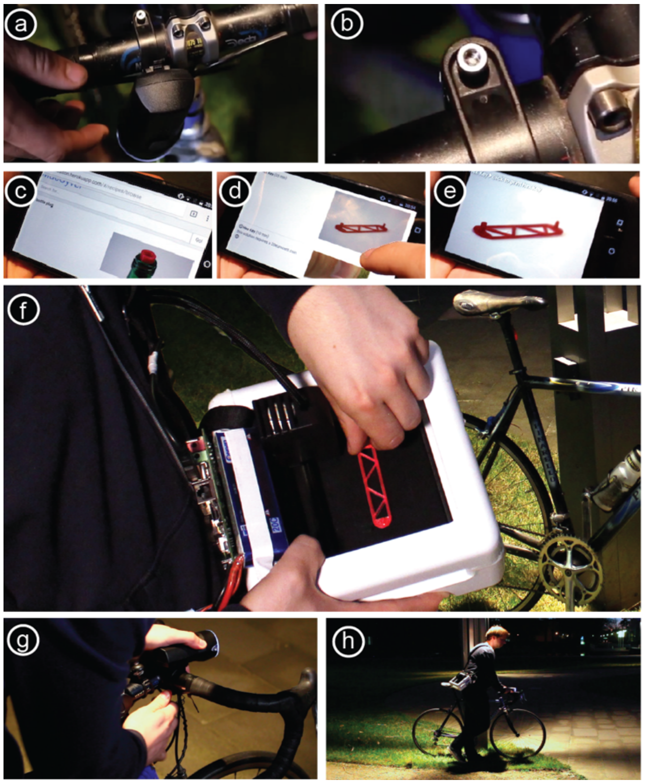

Figure 3: Walkthrough. (a,b) The user wants to go for a nightly bike ride. He finds that his bike lamp is sagging. Fixing it requires a hex key. (c,d,e) He opens our custom app to search for a solution. (f) He prints the solution on his portable 3D printer. (g,h) He fixes the lamp and rides off.

(c) Reinforce weak points. The weakest point of the hex key design is the connection between handle and tip. We reinforce it by adding a smooth transition, aka a *fillet.*

(d) Reinforce using metal parts. If we need to transmit even more torque, e.g., to unlock rusty nuts, make users embed metal objects they are likely to carry, here a coin.

(e) To maximize strength, we print this hex key sideways. This allows filament to weave back and forth between the top and the cradle for the coin, resulting in extra stability.

More challenging was the fabrication of objects that require printing around or through objects from the environment. Shoelaces are one example. While we can 3D print shoelaces, the nature of the PLA plastic makes it hard to tie a knot. We would therefore prefer to close up our shoelaces by 3D printing stoppers at each end, i.e., print, pause the printer to insert the lace into the shoe, *and then* finish the print (as demonstrated in [39] and [3]).

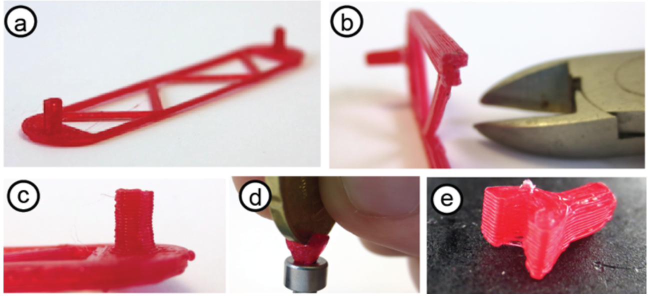

Figure 4: Our optimizations, at the example of the hex key included (a) truss-based geometry, (b) 2½D cross sections, (c) fillet, and (d) embedding a coin for extra stiffness (e) printed sideways for extra strength.

We were able to avoid this type of complication by adding 3D printed locking mechanism into our objects, i.e., print the entire object, insert it, and then close the mechanism. Figure 5 illustrates this, implementing (a) shoelaces as a zip tie and (b) a chain link as a carabiner.

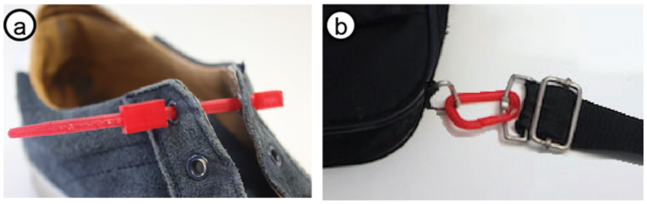

Figure 5: (a) Shoelace as zip tie, (b) chain link as carabiner.

Limitation: Objects that have to fit the environment

While we managed to overcome the challenge of making objects that "loosely" connect with the environment, objects that "tightly" interact with the environment remain elusive.

The hex key from our walkthrough is a benevolent subcategory of this problem. While the user has to guess the size of the nut the hex nuts are standardized. This leaves a reasonably small number of choices, which we can address by simply implementing all the choices under consideration, i.e., a 5mm head *and* a 6mm head. In this particular example, we can do so with little overhead as most of the printing effort goes into the handle regardless.

The overhead of producing multiple solutions, however, grows with the number of possible choices and the approach fails when trying to reproduce an infinite number of choices, such as ear buds that fit the 3D geometry of the user's ear.

Ultimately, mobile 3D printers will likely contain appropriate measurement tools in order to fabricate this class of objects. Measurement equipment could be as simple as calipers or as complex as a 3D scanner with sub-millimeter precision. We discuss this in the discussion section.

Since this type of scanning equipment is not quite ready for mobile use, we took a different approach and created a second mobile fabrication prototype that drops the 3D printer in favor of a more experimental, more flexible fabrication device.

ENGINEERING & PRACTICALITY CHECK 2: HAND-HELD

Figure 6 shows our second prototype. Like our first prototype, it used a plastic extruder. However, instead of the 3D printer's x/y/z actuation mechanism, this prototype was built around a *hand-held* plastic extruder pen, i.e., the prototype actuates the extruder using the user's hand, resulting in a *human-assisted* [41] fabrication system.

Figure 6: (a) Our second prototype was based on a hand-held extruder pen (*3Doodler*) retrofitted with a battery pack for mobile use. (b) We made an additional cap to allow users to put the device back into their pocket while still hot.

At the expense of additional user effort, the ad-hoc benefits of the human-assisted approach include: (1) fabrication directly onto objects in their environments, (2) a device 10x smaller than our first prototype, and (3) substantially faster fabrication (by integrating external objects and a coarser extruder)

Again we wrote an app around the device that provides users with solutions for common problems, and then tried to fabricate the list of desired objects from our survey. We re-engineered all objects so as to produce as fast as possible. Our overall objective was to explore what objects we could make and where our system would fail in order to derive implications for mobile 3D printer hardware, like in the first iteration.

The second prototype

For this prototype, we modified an off-the-shelf plastic extruder pen (a *3Doodler 2.0, the3doodler.com*) to allow for mobile use (Figure 6). It was outfitted with two 120mAH rechargeable batteries to provide 20 minutes of printing time, enough to build one large object or three smaller ones. (Other extruder pens, such as the Creopop (creopop.com) or Bondic (notaglue.com) could have been used as well).

Like our first prototype, plastic extruder pens are based on FDM, which allows them to print in any orientation as well as while shaking. The 3Doodler 2 is 16cm long, allowing it to fit into a coat pocket and is weighs 60 grams including one strand of filament.

The app lets users prototype directly on the phone's screen, utilizing the screen as the build platform to trace blueprints at actual scale. To assure adhesion between filament and screen we covered the screen with adhesive transparent plastic film (0,3mm rigid-PVC, anti-reflex).

The app provided users with solutions for the scenarios from our survey. However, this time the app did not return 3D models, but fabrication instruction to be executed by a human (similar to, for example, *Instructables.com*). The app used the same back-end as our previous app.

Walkthrough

The walkthrough shown in Figure 7 demonstrates the same scenario as before, i.e., how to re-attach a bike headlight using a fabricated hex key. (a) As with our first prototype, the user pulls out the phone and queries the app for "hex key". (b) The app returns multiple results from its online database, each result containing a sequence of instructions to be executed by a human. The first result requires a coin, which our user does not have on him. He thus picks the second hit. (c) The app displays a brief synopsis. The user inspects it briefly to get an overview of what is ahead and flicks to get started.

(d) The app displays the first fabrication step; it shows how to manufacture a truss-shaped handle for the hex key. The system shows the instructions directly on the screen, and the user fabricates the part by tracing it using the extruder pen. The instructions detail how to interlock the individual layers of material to maximize stability. Following additional instructions, the user completes the hex key by (e) molding a tip directly on the nut and (f) fusing it to the handle (details on these techniques below), attaches the light, and rides on.

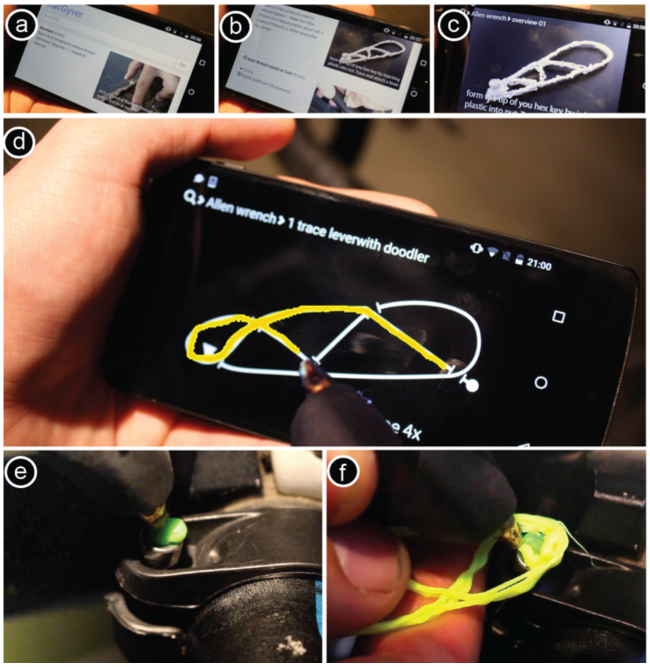

Figure 7: Creating a hex key. (a) The user searches and (b) obtains a list of results. (c) Opening a result shows this object's synopsis. (d) Following the instructions, the user traces a handle, (e) molds a tip, and (f) fuses it to the handle.

Designing for human-assisted mobile fabrication

Our first attempt at creating instructions was in direct analogy to our first prototype: we wrote a script that took 3D models from a repository, ran the results through a slicer, converted the resulting g-code to a drawing format (svg), and displayed it on the phone, for users to trace.

This naïve approach failed on several levels. As immediately obvious, it fails because human-assisted fabrication is less accurate than 3D printing, often making it hard to impossible to recreate relevant details. Figure 8b illustrates this as the tip of the hex key was too imprecise for the key to work.

But more elaborate conversion methods that might try to reengineer the object would be likely to fail, because 3D models tend to lack any information that could be helpful for reengineering the object. Figure 8a illustrates this. The shape of this traditional metal hex key is the result of a die designed to impart a hexagon cross-section into a piece of steel wire, followed by bending and shearing. The 3D printable models we found online imitated this shape literarily, even though the handle's shape in this model was merely reminiscent of the original, forming a skeuomorphism. So while the 3D models give testimony of the machines that produced the original metal key, reengineering the model requires very different information, such as the forces the key is supposed to withstand, crucial shape features, and which parts require what level of precision. This information, however, is missing. We conclude that the attempt to convert 3D models automatically does not offer too much promise.

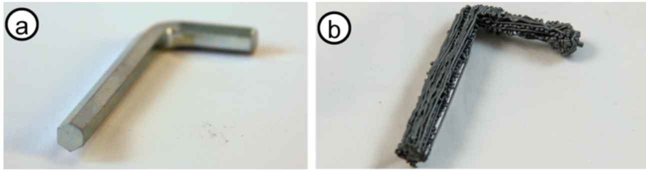

Figure 8: (a) Commercially produced steel hex key. (b) Result of naïve conversion of 3D model, manufactured by tracing.

We therefore re-engineered objects. (1) We broke down commercially fabricated solutions into functional elements and specified the requirements for each element. The metal hex key, for example, though it is a single part, embodies three functional elements: a hexagonal tip, a handle that serves as lever, and something that connects the tip to the lever. (2) We designed techniques that allowed us to re-implement each of the functional elements with the extruder pen. We created a number of five techniques this way (see below). (3) We applied these techniques to the objects from our list. As shown in Figure 9, re-implementing the hex key involved tracing the handle, molding the tip, and fusing the tip to the handle.

In the following we present these five techniques. As with our first prototype, these techniques were created with a team of three lab members with the objective of recreating the objects from the survey. This time we optimized for speed and accuracy in addition to minimal material use and maximum "printing" speed.

1. Replace 3D printing with tracing. As already shown in the walkthrough, our human-assisted prototype uses tracing as substitute for 3D printing. Extruded 2D designs are particularly easy to produce. As illustrated by Figure 9, we therefore try to decompose 3D objects into extruded 2D objects, here handle and tip, which we then "fuse" (see section "Fuse objects to lock them into place").

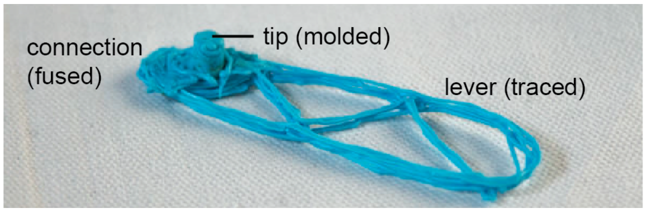

Figure 9: The hex key from the walkthrough consists of 2D parts that are easy to fabricate.

True 2½D objects are harder to fabricate, as the first layer tends to occlude the lines users are supposed to trace when creating subsequent layers. As illustrated by Figure 10, we hint at occluded lines using techniques designed for off-screen visualization, such as dashes (wedge [10]) and rings (halo [1]).

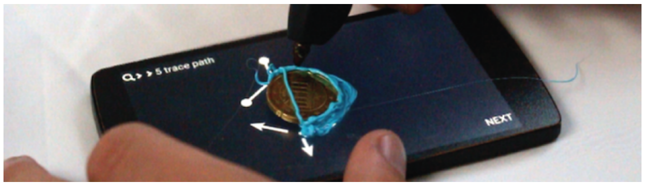

Figure 10: Revealing occluded tracing lines by extending them past the outline of the occluding filament (coin holder).

2. Mold objects to make them fit the environment. This process, which was hard to accomplish using our first hardware prototype, is easy for the human-assisted prototype. As illustrated by Figure 11a, we squeeze material directly onto/into objects in the environment—essentially injection molding. This results in the tightest possible fit and thus best ability to transmit torque for objects, such as wrenches, screwdrivers, bottle openers, keys, and knobs. The extruder pen's ABS material does not stick well to surfaces other than ABS, making it easy to remove the molded parts afterwards.

3. Reinforce objects using metal (and other) parts. The same way we can mold plastic into objects, we can mold objects into plastic. Figure 11b recreates the coin-based hex key by pressing a coin into freshly extruded plastic.

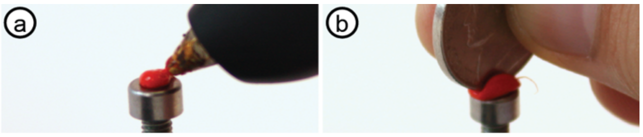

Figure 11: (a) injection molding into a hex screw (b) adding a coin to allow tightening hex nuts with higher torque.

We can also reinforce using non-metal objects. Figure 12 uses a raw strand of filament to re-implement the shoelaces we had already discussed with our first hardware prototype. The use of the raw filament stick is fast, stronger than extruded filament, and allows for further processing using the extruder pen; here the user adds stops at both ends, then prunes the strand using the extruder pen.

Figure 12: A raw strand of filament with extruded stops as improvised shoelace.

4. Needle and thread connect to fabrics Pulling the extruder pen away while extruding produces a thin thread. Pulling even faster causes the thread to rip, leaving a pointy tip (similar to printed hair [15]). In Figure 13, we use the result as needle and thread. We extrude a needle with thread, poke the needle through the shirt cuff, create a button by tracing, and fuse it to the thread to lock it in place.

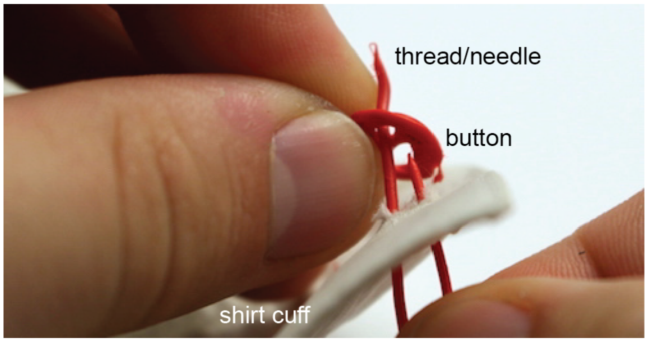

Figure 13: Using extruded filament as needle and thread to attach a button to this shift cuff.

5. Fuse objects to lock them into place. In order to fuse two or more parts, we melt the two sides using the hot tip of the pen and push them together. For extra stability, we reinforce the connection with additional material (Figure 14).

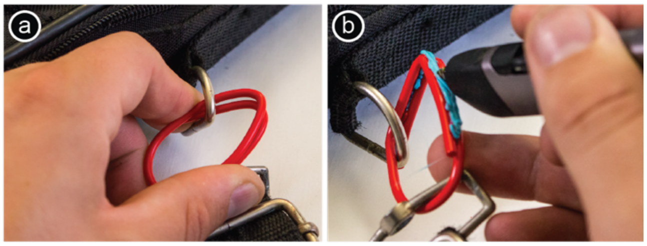

Figure 14: (a) We reattach a bag strap by forming a raw piece of filament into a link and (b) fusing the filament.

Fusing also allows us to create object larger than a phone screen by breaking them down as illustrated by Figure 15. However, this comes at a cost of time and thus fits less well when it comes to urgent solutions.

Figure 15: Creating flip-flops, one screen-full at a time.

Editor

As we already saw in Figure 7, instructions in our app are essentially sequences of photos, making them easy to create. To simplify the creation of instructions even further we implemented the basic editor shown in Figure 16. (a) It offers templates for each of the individual fabrication processes and (b) helps users create instructions to be traced by allowing them to scale photographs with rulers and grid tools as reference, before (c) drawing the lines to be traced on top of the photo.

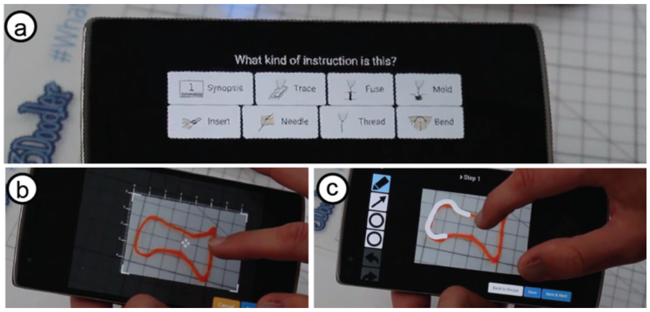

Figure 16: Editor (a) process templates, (b) scaling, and (c) drawing lines to be traced.

USER STUDY

In order to try out mobile fabrication in actual use, we conducted a user study. To recreate a realistic context of use we conducted the study on a metro train. To assure a broad spread in participants' backgrounds we also recruited participants on the train. Every participant was given the extruder-pen based prototype, as well as two objects that required fixing. We gave participants access to the solution database only for one of the two objects. This allowed us to test the assumption brought up by the aforementioned survey participants who had argued that non-engineer require such support.

This study arguably subsumes studies we could have run with our first prototype, as the search interaction was comparable and the 3D printing itself would not have required any particular skill. We thus refrained from running a separate study evaluating the first hardware prototype.

Interface conditions

There were two interface conditions. In the *instruction* condition, participants received an extruder pen (3Doodler 2), a phone (Nexus 5) with access to our solution database, 10 strands of filament. In addition, we invited them to use any objects they had on them.

In the *unassisted* condition, participants received the same hardware, but were not allowed to turn the phone on. This prevented them from searching the database and required them to come up with their own solution. While still enabling them to use the phone as build platform.

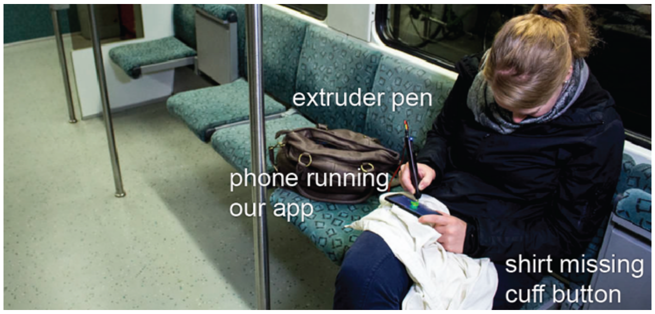

Figure 17: We conducted the study in situ on a metro train.

Tasks

For each task, the broken objects shown in Figure 18 with the instruction to fix it.

Figure 18: Participants performed three tasks: (a) replacing a button on a shirt, (b) replacing broken shoelaces, (c) unscrewing a hex screw.

The *shoelaces task* required participants to create and install improvised shoelaces. In the *instruction* condition, instructions suggested inserting a strand of raw filament into the eyelids, fabricate two stops on object, and cutting the filament as previously shown in Figure 12. The *button task* required users to create a button and attach it to the cuff of a shirt. The *instruction* condition, suggested the needle-and-thread solution shown in Figure 13. The *hex key task*, finally, required users to secure the seat of a foldable chair by tightening a hex screw. In the *instruction* condition, instructions included the coin-based design from Figure 11 and the truss-based design from Figure 9.

Task was a between-subjects variable, i.e., each participant performed one tasks in the *instruction* condition and one task in the *unassisted* condition, in counterbalanced order.

At the beginning of the study, participants received a 5min introduction to the extruder pen and its use during which they doodled on the phone screen. Participants neither received introductions on how to use the phone nor on how to use the app. After the experiment, participants filled in a questionnaire and commented on the system's usability and issues. Participants completed the study in 30min or less.

Participants

We recruited twelve participants on the train (age 18-52). None of the participants had ever used a 3Doodler before nor did they have experience with 3D printing. We rewarded participants with a small snack.

Results

Human-assisted fabrication is useful. As shown in Figure 19a, participants' satisfaction with the extruder pen + app system (i.e., the *instructions* condition) was high. Participants rated "the pen helped me solve the problem" as 5.6/7, "I am happy with the solution" as 5.4/7, and "I enjoyed using the system" 6.4/7. Participant 4 asked: *"this was very cool, can I buy/use this system"?* Two participants did not even mind missing their train stop because they wanted to do more of this. Of course a strong novelty effect plays a role here. Participants rated *"the solution database helped me solve the problem"* with 5.8/7.

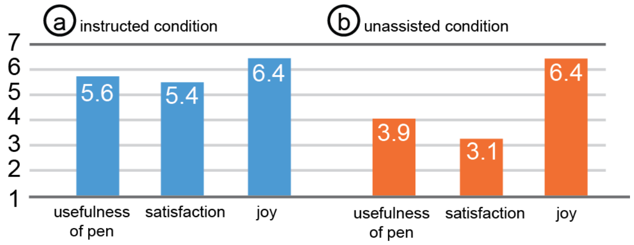

Figure 19: (a) Participants rated the pen as useful, their experience as enjoyable, and their results as satisfying (b) unless we took away their access to the solutions database.

…but only with instructions. This was *not* the case for the *unassisted* condition (Figure 19b). While the overall enjoyment of using the system was the same as for the *instruction* condition (6.4/7), participants rated the pen as much less useful (3.9/7) and participants generally were much less happy with the solution they had produced (3.1/7). This agrees with our assessment of the quality of participants' solutions.

A key factor responsible for the lower ratings clearly was that fixing the three objects without the solution database required engineering skill, which participants did not have. While several participants, for example, figured out how to mold plastic into the hex nut, they all failed to create and attach a matching handle. This was worsened by participants' lack of up-front planning, i.e., they started by fabricating the most obvious, but non-functional element, such as a button or shoelaces and then they struggled with attaching these parts.

Human-assisted fabrication can be faster than 3D printing. Participants produced the hex key on average in 4:37min including search time (5.4x faster than our 3D printer, which required 25min to make a comparable object), made and mounted the button in 5:33min (2.7x faster our 3D printer which took 15min), and replaced shoelaces in 3:31min (5.7x faster than our 3D printer, which took 21min). Part of the substantial speedup resulted from the reuse of ready-made objects, here the raw strand of filament and the coin.

Following instructions step-by-step vs. skimming. The study also provided us with some usability insights. In particular, only half of the participants (6/12) followed the instructions steps by step. All other participants flicked through the images of the instructions only briefly, before starting their own exploration. The brief browsing was apparently sufficient to allow them to produce functional, if perhaps occasionally suboptimal results. At the time of the study, instructions did not yet include a synopsis page; to better support users who prefer to skim, we added it (Figure 7c).

Discussion

Overall, our findings suggest that human assisted fabrication works with non-engineers. However, access to a solution database is crucial, as the type of impromptu problem solving that is characteristic for mobile fabrication tends to exceed the ability of non-engineers. At the same time, the good results in the *instructions* condition suggest that access to an online database is an appropriate tool for overcoming this hurdle.

DISCUSSION: MOBILE FAB TODAY & TOMORROW

In the sections above, we explored mobile fabrication as we are able to implement it today. We learned:

1. There are on-the-go scenarios worth addressing. In our surveys, participants listed 75 objects of which 50 could be fabricated. The most popular scenarios where *make a key when you locked yourself out* and *making a wrench to fix your bike lamp*.

2. Current technology is able to produce many of these objects: 3D models need to be re-engineered for mobile fabrication; we demonstrated how to do this. We found that human-assisted fabrication does better at connecting to the environment and avoiding measurement.

3. Human-assisted fab works for non-experts and is even enjoyable, as our study showed. However, access to a solution database is crucial.

We also learned about the strength and limitations of two different approaches to mobile fabrication hardware. The extruder pen obviously requires additional user effort and more skill than the 3D printer-based approach. However, the extruder pen approach also offers a number of benefits. (1) The use of the extruder directly on objects in the environment helps create objects that fit the environment. This was the main pain point with printer-based fabrication. (2) Since the extruder pen technology does not even aim for precision, it can extrude filament in thicker lines, allowing it to fabricate substantially faster. The use of ready-made parts, such as strands of raw filament offers additional speed-ups. (3) The pen allows for a substantially smaller form factor (no x/y/z actuator, no server, and smaller batteries). (4) Fusing parts allows extruder pens to make larger objects, while 3D printers are limited by their build volume.

Since both approaches have their strengths we would expect future mobile fab systems to try to combine the qualities of both approaches.

Future mobile fabrication hardware

So what will future mobile fab systems look like? First, such a device may include what worked well for both our approaches: (1) *Solutions database* offering solutions specifically for on the go scenarios. *(2) Control using mobile phones* as users already carry these. *(3) Design of a "balanced" machine.* When we designed our devices, we started by defining the maximum object size we wanted to support. This decision then informed all other design decisions, such as how much material to store, how much battery power to include, and how large to make the print volume.

Finally, *additive fabrication* was probably a reasonable choice too, as subtractive fabrication requires carrying excess material. And even though FDM is a slow process, it may at least for now be better suited than arguably more advanced process, such as stereolithography based on projection (e.g., *Form1(formlabs.com)*, *Carbon3D(.com)*, and *Olo* (*olo3d.com*)), as their tank of resin has to be stationary during use.

However, FDM itself still offers potential for optimization. In particular, devices that *extrude* a photo curable resin might be a step forward. Given that the material itself stores the energy required to harden, this process tends to allow for faster fabrication than extruding plastic. It also works with smaller batteries allowing for an even more compact form factor. Figure 20 illustrates this at the example of a commercial hand-held extruder based on UV curable plastic (*Bondic* (notaglue.com), 13cm long, weighs 16g). We could make the same objects as with the plastic extruder pen.

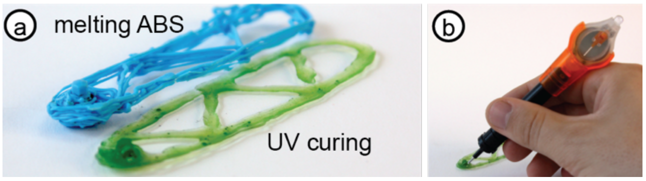

Figure 20: The hex key fabricated using a UV curing pen (*Bondic*).

Based on these fundamental design choices, we would expect future mobile fabrication devices to combine the qualities of our two prototypes with:

1. Included 3D scanner. In order to allow future devices to be automated like our first prototype (which also comes with higher precision and reliability), and subsume the pen-based system they will probably include a 3D scanner to make objects that connect to the environment. The scanner may be contained in the printer [30] or in the phone.

2. Build on a robotic arm. One of the key benefits of our hand-held prototype was its ability to produce reasonably large objects despite its tiny size (Figure 21a). In order to provide this benefit in the context of an automated device, future devices may be based on a small robotic arm (Figure 21b). Additionally, it would allow for on-object fabrication.

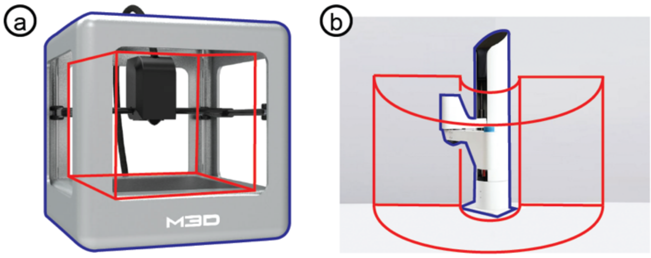

Figure 21: (a) Cartesian 3D printers are larger than the print volume they support. (b) A robotic arm supporting a comparable print volume can be substantially smaller. (*makerarm.com*)

Figure 22 shows one of many such possible future designs.

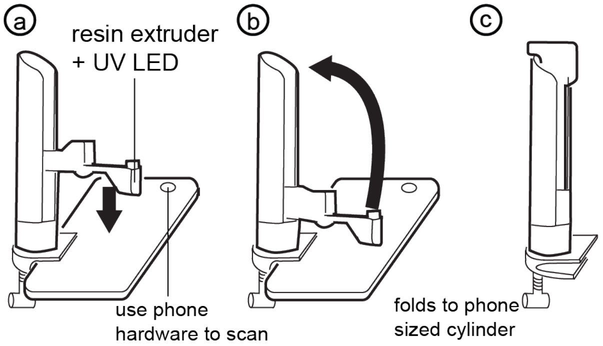

Figure 22: (a) Mock-up of one possible future mobile fabrication device that clips onto the phone as build platform and attaches to surfaces to produce directly on them. (c) Folded up to fit in a pocket.

CONTRIBUTION & CONCLUSIONS

Our main contribution is an exploration into the future of fabrication, in particular the vision of mobile fabrication. We explore this vision with two surveys, two simple hardware prototypes, matching custom apps that provide users with access to a solution database, engineering fabrication techniques specifically for these devices, including tracing and molding, and a user study conducted in situ on metro trains. All of this combined asks the question whether mobile fabrication will happen. We think it will.

As future work, we plan to engineer such devices, including the design shown in Figure 22.

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