Interacting with personal fabrication devices

1 Introduction

With the recent price drop in 3D printing hardware, personal fabrication tools are about to enter the mass market [1]: While in 2007, the average consumer 3D printer was priced at $14,000, today’s hardware costs only around $500 on average [16].

However, while more and more users now have access to the technology, the interaction model is still targeted at expert users [12]. In today's interaction model (Fig. 1), users sit at a computer and use a 3D editor to create a digital 3D model. Only at the end of the design process, users send the file to the 3D printer to create the physical version, which is fabricated in one-go. Since 3D printing is slow, this tends to take hours of printing time for small objects or even requires printing overnight.

Consequently, the current interaction model requires users to think carefully before printing as every mistake may imply another overnight print. This is not feasible for non-technical users as they lack the experience to reason about the consequences of their decisions [13].

Looking back in history, this interaction model with the delayed feedback was also common with early computers [3]. In the early ’60s, computers were so slow that the average program had to be executed overnight. Feedback was delayed until the next morning and if a program failed, users had to repeat the entire process, potentially waiting another night. Similar to 3D printers today, early computers were limited to expert users because when programs were executed in one-go overnight, users had to be experts in what they were doing in order to succeed.

However, today we are at a point at which even non-technical users can use a personal computer. Beside many
technical developments, two advances in the interaction model enabled this [6]: (1) the move from executing in one-go to turn-taking, and (2) the move from turn-taking to direct manipulation (see Figure 2):

(1) *Turn-taking:* By decreasing the interaction unit from entire objects to single requests, turn-taking systems such as the command line evolved, which provided users with feedback not at the end but after every input. This enabled the trial and error process non-technical users tend to employ: quickly iterating through potential solutions and building each step onto the results of previous ones [4]. As a side effect, this new exploratory interaction model also allowed for more unconventional solutions as the potential cost of a step not working out was reduced. However, while the turn-taking interaction model provided a great step forward to making the technology available for non-technical users, the feedback-cycle was still limited in that it consisted of two discrete steps: users first had to create an input and only afterwards received feedback—this introduced wait time during testing and limited users to testing only a few discrete solutions among an often continuous spectrum (e.g., testing only a few values rather than continuously browsing the space with a slider).

*Direct manipulation:* By decreasing the interaction unit further from single requests to single features, users finally received real-time feedback, thereby enabling direct manipulation [13]: Input by the user and output by the system are so tightly coupled that no visible lag exists. This tightened feedback cycle has many benefits, among others that 'novices can learn basic functionality quickly' and 'retain operational concepts' [14].

As described above, the current interaction model of 3D printers requires objects to be fabricated in one go. Thus, from a human-computer interaction standpoint, we are today at the point at which we were with personal computers in the 1960s: Only few users are able to use the technology and even for experts it is a cumbersome process due to the delayed feedback.

Recently, Willis et al. argued that by repeating the evolution of the interaction model from personal computing, we will see the same benefits for personal fabrication. With a concept called Interactive Fabrication [15], Willis et al. propose that by bringing direct manipulation principles to personal fabrication tools, non-technical users will be able to create physical objects as easily as they manipulate digital data with today’s personal computers.

How an interactive fabrication system works can best be pictured by envisioning a craftsman working with a physical tool on a physical workpiece, such as a piece of clay. Every ‘input’ by the tool, results in immediate physical ‘output’, i.e., change of the workpiece. The difference between traditional crafting and interactive fabrication is that the tool is no longer analog but digitally enhanced by a computer system. This eliminates the need for skill and provides the user with advanced functions, such as creating perfectly straight lines, the ability to replicate physical structures by copying and pasting them across the workpiece, or to undo the last step. While a few prototype systems, such as Shaper [15] and CopyCAD [5] have been built, no systematic exploration of how to achieve interactive fabrication systems with continuous physical feedback exists.

In the following three sections, we will step-by-step walk through the three development stages of the user interface for personal computing as illustrated in Fig. 2 and will describe a set of systems we built to mirror this development in personal fabrication.

2 Fabricating in one-go

As pointed out in the introduction, today’s 3D printers are so slow that fabricating slightly larger objects requires overnight printing. The head mounted display body in Fig. 3c, for instance, took 14:30 hours printing time on our 3D printer (Dimension SST 1200es). When designing a new object, which typically requires going through a series of iterations, this slows down the feedback cycle to one iteration per day.

To provide faster feedback, we take an approach inspired by early computer graphics: When computing was slow, researchers proposed a method for rendering content with different levels of detail to give users a fast preview. The key idea was to render only the important parts of a scene as slow high-fidelity and to render everything else in fast low-fidelity. This approach scales well as users tend to focus on only one part at a time.
Similarly, when prototyping users typically focus on one aspect of the design at a time. For instance, users might want to verify that each part of the object functions properly, then move on to get the overall look and feel right.

By applying the principle of different levels of detail to fabrication, we can fabricate the parts that are currently not being tested as fast low-fidelity, and reduce high-quality printing to only the parts that need detailed evaluation. This allows us to get a testable version faster, thereby tightening the feedback-cycle during design iteration. We call this concept of printing intermediate versions as low-fidelity prototypes *low-fidelity fabrication* [7]. Fig. 3 shows three example implementations of low-fidelity fabrication: *WirePrint* [8] preserves an object’s shape for testing ergonomics and fit while being up to 90% faster, *Platener* [2] allows to test functional objects quickly by converting 3D models into 2D parts that can be fabricated on a fast laser cutter, and *faBrickation* [10] allows for very modular design by combining 3D printing with existing building blocks.

### 3 Turn-taking

While low-fidelity fabrication allows users to create, test, and redo objects quickly, redoing an object in its entirety is not necessarily the most effective approach. Arguably, feedback is most beneficial when making key design decisions along the way. Turn-taking interfaces offer this affordance by providing fast request and response transactions: users first create an input and receive an answer from the system within seconds. This tightened feedback loop allows users to iterate towards a final solution through trial-and-error by building subsequent steps onto the results of previous ones.

To transition from the low-fidelity fabrication systems that fabricate an object in one go to turn-taking system with a request and response interaction, we decrease the interaction unit to a single element of an object, such as one line. To illustrate turn-taking for personal fabrication, we build a system called *constructable* [9].

*constructable* is based on a laser cutter that produces precise physical output after every editing step. As illustrated by Fig. 4, all interaction in constructable takes place on the work-piece inside the laser cutter, mediated through hand-held laser pointers, which represent different tools. In the example in Fig. 4, the user uses the finger joint tool to add finger joints between two pieces by crossing the two involved edges.

### 4 Direct manipulation

By decreasing the interaction unit even further to a single feature, we can achieve continuous physical feedback, i.e., with one interaction users can explore the entire space of shapes, potentially leading to a better result in less time. This is in contrast to the turn-taking systems shown in the previous chapter that consist of two discrete steps, i.e., users first create an input, and then the system responds with physical output, which only allows to explore one option per turn.

Our system *FormFab* [11] illustrates this—it reshapes a work-piece using the following process (Fig. 5): A heat gun attached to a robotic arm warms up a thermoplastic sheet...
Figure 5: FormFab provides continuous physical feedback. As users move their hand, they see the shape change in real time.

until it becomes compliant; users then interactively control a pneumatic system that applies either pressure or vacuum thereby pushing the material outwards or pulling it inwards. As users interact, they see the workpiece change continuously and in real-time.

FormFab’s user interaction consists of two steps. In the first step, users use their index finger to draw an outline of the area they want to reshape onto the workpiece. When the user removes the hand from the workpiece, the path is beautified by our software. The robotic arm then starts warming up the area using a heat gun.

After the material has reached its compliance point, the robotic arm moves out of the way and the user starts the second step: By performing a pinch gesture above the workpiece, the pneumatic system increases the air pressure and the user sees the compliant area inflate continuously and in real-time. If the user’s hand moves back towards the workpiece, the pneumatic system reduces the pressure and the user sees the compliant area deflate.

While step 1 of the user interaction, i.e., drawing the outline, still follows the turn-taking interaction model, step 2, i.e., defining the extrusion amount provides continuous physical feedback: input by the user and output by the fabrication device are coupled tightly allowing for continuous interaction.

5 Summary and conclusions

In this article, we argued that by repeating the evolution of the interaction model from personal computing, we will see the same benefits for personal fabrication. Figure 6 illustrates how we explored interfaces for personal fabrication that follow the evolution of personal computing:

Figure 6: Following the evolution of personal computing, we developed systems that (a) fabricate objects quickly in one go, (b) provide physical feedback after every editing step, and (c) allow users to change the shape of an object in real-time.

We started with fabricating objects in one go and investigated how to tighten the feedback-cycle on an object-level. We showed how our method low-fidelity fabrication saves up to 90% printing time while allowing users to focus on different key aspects, such as modularity (fabRicker [10]), shape (WirePrint [8]), and function (Platener [2]).

Next, we decreased the interaction unit to a single element of an object to explore what it means to transition from systems that fabricate in one go to turn-taking systems for personal fabrication. We showed a system called constructable [9] that demonstrates how users can interactively create objects while receiving physical feedback after every editing step.

Finally, by decreasing the interaction unit even further to a single feature, we showed how to achieve continuous physical feedback, thereby moving from turn-taking interfaces towards direct manipulation. We demonstrated how our system FormFab [11] allows users to create input to the system while continuously receiving physical feedback.
References

1. Baudisch, P. and Mueller, S. “Personal Fabrication”, Foundations and Trends® in Human–Computer Interaction: (2017), vol. 10: no. 3–4, pp. 165–293.
2. Beyer, D., Gurevich, S., Mueller, S., Chen, H.-T., Baudisch, P. Platener: Low-Fidelity Fabrication of 3D Objects by Substituting 3D Print with Laser-Cut Plates. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI ’15), 1799–1806.
3. Ceruzzi, P. A history of modern computing. In The MIT Press, 2nd edition (2003).
4. Csikszentmihalyi, M. Flow: The psychology of optimal experience. In Harper Perennial Modern Classics (2008).
5. Follmer, S., Carr, D., Lovell, E., Hiroshi, I. “CopyCAD: Remixing Physical Objects with Copy and Paste from the Real World”. In Adjunct Proceedings of the 23rd Annual ACM Symposium on User Interface Software and Technology (UIST ’10), 381–382.
6. Grudin, J. A moving target—the evolution of human-computer interaction. In Human–Computer Interaction Handbook, 3rd Edition, Taylor and Francis (2012).
7. Mueller, S. and Baudisch, P. Low-Fidelity Fabrication: Speeding up Design Iteration of 3D Objects”. In Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA ’15), 327–330.
8. Mueller, S., Im, S., Guerevich, S., Teibrich, A., Pfisterer, L., Guimbetiere, F., Baudisch, P. WirePrint: Fast 3D Printed Previews. In Proceedings of the 27th annual ACM symposium on User interface software and technology (UIST ’14), 273–280.
9. Mueller, S., Lopes, P., Baudisch, P. “Interactive Construction: Interactive Fabrication of Functioning Mechanical Devices”. In Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology (UIST ’12), 599–606.
10. Mueller, S., Mohr, T., Guenther, K., Frohnhofen, J., Baudisch, P. “faBrickation: Fast 3D Printing of Functioning Objects by Integrating Construction Kit Building Blocks”. In Proceedings of the 32nd Annual ACM Conference on Human Factors in Computing Systems (CHI’14), 3827–3834.
11. Mueller, S., Seufert, A., Peng, H., Kovacs, R., Reuss, K., Wollowski, T., Guimbetiere, F., Baudisch, P. Tightly Coupled Interactive Fabrication: Bringing the ability to explore a design space into personal fabrication. submitted to TOCHI 2018.
12. Schmidt, R., Ratto, M. Design-to-Fabricate: Maker Hard ware Requires Maker Software. In IEEE Computer Graphics and Applications (2013), vol. 33, issue 6, pp. 26–34.
13. Shneiderman, B. “Direct Manipulation: A Step Beyond Programming Languages”. In Computer (1983), vol. 16, issue 8, pp. 57–69.

14. Shneiderman, B. The future of interactive systems and the emergence of direct manipulation. In Proceedings of the NYU Symposium on User Interfaces on Human Factors and Interactive Computer Systems (1984), 1–28.
15. Willis, K. D. D., Xu, C., Wu, J. K., Levin, G., Gross, M. D. “Interactive Fabrication: New Interfaces for Digital Fabrication”. In Proceedings of the fifth International Conference on Tangible, Embedded, and Embodied Interaction (TEI ’11), 69–72.
16. Wohlers Associates. Wohlers Report: 3D Printing and Additive Manufacturing State of the Industry. Annual Worldwide Progress Report, 2017.

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