Introduction to Personal Fabrication
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Process Documentation in
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What is Personal Fabrication?
How can we empower everyone to create physical objects with ease?
Digital Fabrication
Digital fabrication tools turn bits into atoms, i.e. they create material objects from digital designs.

- Catarina Mota, The Rise of Personal Fabrication, C&C’11
Autodesk Fusion 360
Digital fabrication tools turn bits into atoms, i.e. they create **material objects** from **digital designs**.

- Catarina Mota, The Rise of Personal Fabrication, C&C’11
Subtractive Manufacturing
Additive Manufacturing
**What is a fab lab?**
Fab labs are a global network of local labs, enabling invention by providing access to tools for digital fabrication.

**What’s in a fab lab?**
Fab labs share an evolving inventory of core capabilities to make (almost) anything, allowing people and projects to be shared.

**What does the fab lab network provide?**
Operational, educational, technical, financial, and logistical assistance beyond what’s available within one lab.

**Who can use a fab lab?**
Fab labs are available as a community resource, offering open access for individuals as well as scheduled access for programs.

**What are your responsibilities?**
- Safety: not hurting people or machines
- Operations: assisting with cleaning, maintaining, and improving the lab
- Knowledge: contributing to documentation and instruction

**Who owns fab lab inventions?**
Designs and processes developed in fab labs can be protected and sold however an inventor chooses, but should remain available for individuals to use and learn from.

**How can businesses use a fab lab?**
Commercial activities can be prototyped and incubated in a fab lab, but they must not conflict with other uses, they should grow beyond rather than within the lab, and they are expected to benefit the inventors, labs, and networks that contribute to their success.

[http://fab.cba.mit.edu/about/charter/](http://fab.cba.mit.edu/about/charter/)
Who can use a fab lab?
Fab labs are available as a community resource, offering open access for individuals as well as scheduled access for programs.
How do we connect this to HCI research?
Official Creality3D Ender 3 DIY 3D Printer Kit

Creality3D Ender 3 DIY 3D Printer Kit [220x220x250mm Printing Size With Power Resume Function/MOS Extruder Resume Print: Ender 3 can resume printing even after a power outage or lapse occurs. Easy and Quick Assembly: It comes with seven Item Code: TOPS2-3DP-Ender-3

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https://www.creality3donline.com/creality-ender-3-3d-printer_p0019.html – 3rd June 2019
Visicut

By Thomas Oster
If we go back to the beginnings of interactive computing, early computer users were probably reasonably happy placing their punch cards into the reader and waiting for their output to arrive hours later—which is pretty much where 3D printing stands today.

- Patrick Baudisch, Personal Fabrication in HCI: Trends and Challenges, AVI’16
ReForm: Integrating Physical and Digital Design through Bidirectional Fabrication

Christian Weichel
John Hardy
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From Lancaster University

UIST’15
ReForm

Integrating Physical and Digital Design through Bidirectional Fabrication

video: Robert Potts and Daniel Morrell (Ourus LTD)
Figure 7. The ReForm prototype: (a) a jog wheel for user-input (b) LMI HDI1203D scanner (c) Asus Xtion depth camera (d) heated clay extruder (e) milling spindle (f) build plate (g) projector and screen (h) air-guide (i) ReForm Core.

ReForm Core contains supporting components for the main machine. It houses 12V and 24V power supplies, six CW5405 stepper controllers that are connected to a Linux-CNC powered MiniITX computer through a HW08 IO board. An emergency switch at the front of the ReForm Core cuts the 24V power to the motors if necessary.

ReForm is constructed within an aluminium frame. A spindle and clay extruder pair (Figure 7, d, e) are mounted on an XYZ motion platform. The clay object is attached to a build plate held onto the two rotary axes A/B using ball bearings. A structured light scanner (Figure 7, b) is mounted on the right side of the frame for an unobstructed view of the object. A custom air-guidance system directs an airstream to the workpiece (Figure 7, h).

An archer MV3P vacuum cleaner and a heating element are used to generate the airstream. We use an Arduino-controlled relay to automatically turn the airstream on and off. Situated at the top of the frame is a Xtion depth camera (Figure 7, c) and a short-throw projector for the augmented-reality interface (Figure 7, g). This interface is projected on the articulated front-door which holds a semi-transparent projectionscreen. In front of the machine (outside of the door) users find the jog wheel (Figure 7, a) for interacting with ReForm.

The spindle is based on a 260rpm/V brushless DC motor whose 8mm shaft we replaced with an ER11 collet (Figure 7, e). A 6mm flat-tip two-flute cutter is fitted into the collet. Compared with steeper tip angles, this flat-tip configuration produces non-clogging clay flakes. The motorspeed is controlled from an Arduino through an electronics speed controller (ESC).

We extrude warm TecClay through pressure by actuating a threaded rod plunger in a metal cylinder. Due to the surface friction of the clay (which is reduced by heating the cartridge), a 3.1Nmmotor is required. To reduce the moving mass of the XYZ platform we mount the 1.4kg heavy motor off-axis and transport its rotational movement with a flexible driveshaft to the extruder. This assembly extrudes the clay through a 3mm heated brass nozzle mounted 2mm above the cutter (Figure 7, d).

To 3D scan the object we use an LMI HDI1203D structured light scanner (Figure 7, b) with an accuracy of 60-118 µm. While scanning we take six snapshots; rotating the model by 60° each time around the build-plate center. By using white TecClay we minimize exposure time for each snapshot, so that a 360° scan takes about 1.5 minutes. We use LMI's FlexScan software to align the snapshots and merge them into one 3D mesh model. This scanning process also covers a monochromatic texture which we use for annotation input. A scanned model has approximately 100k vertices.

Augmented Reality Interface

A BenQ W710ST short-throw projector (Figure 7, g) projects on the transparent projectionscreen held in the door. We manually calibrated the virtual camerato match the physical scene, and using an Xtion depth camera (Figure 7, c), we track the user's body to provide a motion-depth cue. This allows us to render aligned virtual 3D previews over the physical clay model.

System Performance

The toolhead can travel at a maximum speed of 45mm/sec along the XY axes, 2mm/sec along Z, 600 deg/sec around the A axis and 30 deg/sec around the B axis. Our clay extrusion system can extrude material at a maximum rate of 1cm³/sec with its cartridge holding 104cm³ of material. When milling, the maximum spindle plungedepth is 4mm. The 3D scanner to machine calibration error is less than 0.15mm.

Toolpath Generation

Bidirectional fabrication requires us to compute machine instructions that transform between two arbitrary digital meshes. The resulting toolpaths describe the motions a machine has to execute in order to add or remove material. To generate additive and subtractive toolpaths we need to determine where to add and where to remove material, and construct the paths themselves. We implemented a novel toolpath generation algorithm, which combines both tasks. The algorithm takes as input the currently existing surface and the toolpath itself. We use these toolpaths to generate the machine instructions.
Bidirectional Fabrication
More targeted operations require the selection of an area of influence. We use annotation input to enable users to mark the area they want to manipulate on the physical object.

Physical Shaping

a) Users can mold a physical object directly and in context. As the material is malleable when heated to approximately 50°C, users can manually add more material. The physical objects can be bent, smeared, and otherwise plied using sticks to itself. Users can manually add more material. The physical objects can also be bent, smeared, and otherwise plied using sticks to itself. Users can manually add more material.

b) Simple tools like knives and cutters can be used to manipulate the physical object (Figure 5, b). Specialized tools can also be used to manipulate the physical object (Figure 5, c). Simple tools like knives and cutters can be used to manipulate the physical object (Figure 5, b). Specialized tools can also be used to manipulate the physical object (Figure 5, c).

c) Users can manually add more material. The physical objects can be bent, smeared, and otherwise plied using sticks to itself. Users can manually add more material. The physical objects can be bent, smeared, and otherwise plied using sticks to itself. Users can manually add more material.
DISCUSSION

Through our implementation and design walkthroughs we learn several practical lessons from realising bidirectional fabrication. Our current implementation solves model-object registration by fixing the object to a build-plate, thus enforcing a fixed reference frame. While this approach simplifies implementation, it also limits what users can do with the physical object — e.g. the side attached to the build-plate cannot be modified. To do away with the build-plate, one could use the Iterative Closest Point algorithm [27] or apply infrared registration markers e.g. spraying an arbitrary dot pattern. However, being able to externally machine an object requires it to be held firmly in position.

The accuracy/fabrication-time trade-off can be tuned at runtime of the system, making it more flexible. If high accuracy is required, the more precise of the two fabrication methods can be used and the machine can move slower. If short fabrication times are desired, a more coarse fabrication method is used at higher speeds. For example, in our prototypes subtractive operations are more precise than additive ones. Thus if accuracy is required, we can refine additively fabricated features subtractively.

Technical Limitations

Due to tolerances of the fabrication process, we can update the object after each physical update and update the digital model accordingly. This can lead to an accumulative error, thus makethemodel degrade over time. A relaxed object/model correspondence, where only desired changes are integrated into the digital model would remedy this problem.

Optical 3D scanners require all parts of the 3D model to be visible to them. Thus, concavities and hollow areas are difficult to capture. By integrating multiple 3D scanners, we could capture the physical object to a greater extent. Similarly, the digital fabrication stage is limited by what it can physically reach. Using all five axes for fabrication would increase the set of fabricable shapes, but also increase the algorithmic toolpath generation complexity.

Alternative Implementations

Other forms of implementing ReForm and bidirectional fabrication are possible. If only one fabrication method were automated, the other method could be performed manually e.g. computer-controlled milling and manual material additions similar to Sculpting by Numbers [16]. Bidirectional fabrication could also be implemented by combining automated construction kit assembly (e.g. LEGO®) utilizing automated brick layout algorithms [21], and some shape-sensing capabilities integrated into the construction kit.

Multi-material printers could be used to implement a bidirectional fabrication process offering a whole new range of interactions. Malleable and hard materials in the same object could be used to express constraints. Built-in curvaturesensor using printed optics [25] would make the artifact itself interactive, or even enable them to sense their own shape.

CONCLUSION

In this paper we introduced bidirectional fabrication; a concept whereby digital and physical objects are entangled so that updates to one always propagate to the other. This enables users to design objects using precise repeatable digital operations, intuitive expressive physical actions, and combinations of both. To evaluate this concept, we built ReForm: a

Scan

Print
The digital fabrication process fundamentally changes the digital fabrication design process. It produces a range of advantages. First, it allows users to choose the best-suited tools for each portion of the process: creative, expressive, and ad-hoc. Second, it enables design to be performed through iterative addition and/or subtraction of material. Third, it permits incremental fabrication of objects with gradual addition of parts or details.

Bidirectional fabrication fundamentally changes the digital fabrication process. It allows users to move flexibly between working on the digital and physical models. This system, called ReForm, supports object versioning to allow visual output. By continually synchronizing the physical object with the virtual model, it allows both digital and physical input, shape output, annotation for machine commands, and production of a rigid separation between work-spaces: the user over to a machine to fabricate the physical object. This setup is rigid and fabricated in a single pass, but can evolve in the process, through iterative addition and/or subtraction of material.

ReForm updates the digital model when the user changes the physical representation, and vice versa, the user changes the digital representation of an object. When an object is fabricated, re-shaping the physical object no longer supports subsequent redesign. This is a problem when the user’s work on the digital model must be completed before fabrication. This results in a one-way design pipeline, where the machine can only influence the physical object, and the user can only manipulate the digital representation of the object. This produces a rigid separation between work-spaces: the user over to a machine to fabricate the physical object. This setup is rigid and fabricated in a single pass, but can evolve in the process, through iterative addition and/or subtraction of material.

Figure 1 illustrates how bidirectional fabrication closes the loop between digital modeling and physical shaping. For example: (a) user has a digital model of a cup, (b) removes the handle, (c) ReForm updates the physical object, (d) user adds a new handle, (e) ReForm updates the digital model.
Smart Makerspace: An Immersive Instructional Space for Physical Tasks

Jarrod Knibbe
Tovi Grossman
George Fitzmaurice

From Autodesk
Research & University of Bristol

ITS’15
Smart Makerspace

An immersive instructional space for physical tasks
Badge Maker
by Moritz Messerschmidt
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