

ReForm: Integrating Physical and Digital Design through Bidirectional Fabrication

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ABSTRACT

Digital fabrication machines such as 3D printers and laser-cutters allow users to produce physical objects based on virtual models. The creation process is currently unidirectional: once an object is fabricated it is separated from its originating virtual model. Consequently, users are tied into digital modeling tools, the virtual design must be completed before fabrication, and once fabricated, re-shaping the physical object no longer influences the digital model. To provide a more flexible design process that allows objects to iteratively evolve through both digital and physical input, we introduce *bidirectional fabrication*. To demonstrate the concept, we built *ReForm*, a system that integrates digital modeling with shape input, shape output, annotation for machine commands, and visual output. By continually synchronizing the physical object and digital model it supports object versioning to allow physical changes to be undone. Through application examples, we demonstrate the benefits of *ReForm* to the digital fabrication process.

Author Keywords

Digital Fabrication; Clay-Modeling; Prototyping; Iterative Design

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION

Digital fabrication enables users to create custom physical objects. The creation process involves two separate tasks: first, the user generates or customises a digital model of the required object in virtual space; second, they hand the model over to a machine, to fabricate the physical object. This setup produces a rigid separation between work-spaces: the user can only manipulate the digital representation of the object, while the machine can only influence the physical object during fabrication. This results in a one-way design pipeline, where the user's work on the digital model must be completed before the hand-off to the machine. Further, the machine's

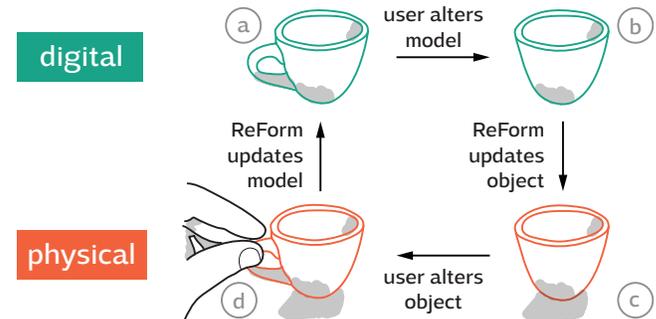


Figure 1. Bidirectional fabrication closes the loop between digital modeling and physical shaping. For example: (a) user has a digital model of a cup, (b) removes the handle (c) ReForm updates the physical object (d) the user adds a new handle to the physical object (e) ReForm updates the digital model.

output is produced in one go, resulting in a rigid form that does not support subsequent redesign.

To overcome the rigidity of the conventional fabrication process, we introduce *bidirectional fabrication*: the ability for the user to move flexibly between working on the digital model and the physical object. Bidirectional fabrication extends digital fabrication in three fundamental ways. First, users are not limited to working on a digital model, but can also shape and annotate the physical object directly. Second, the machine can produce physical forms from digital models *and* use physical shape as input to produce or update corresponding digital models. Third, the physical object is not 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. When the user changes the digital representation of an object, the machine updates the physical representation; and vice versa, when the user changes the physical representation, the machine updates the digital representation.

Bidirectional fabrication fundamentally changes the digital fabrication design process and 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 3D design is easy to perform through direct physical manipulation of an object, while tasks involving precise input or repetition are better done using digital tools. Second, it enables ‘turn-taking’ between the user and machine. This allows each to leverage their respective strengths and permits incremental fabrication of objects with gradual addition of parts or detail.

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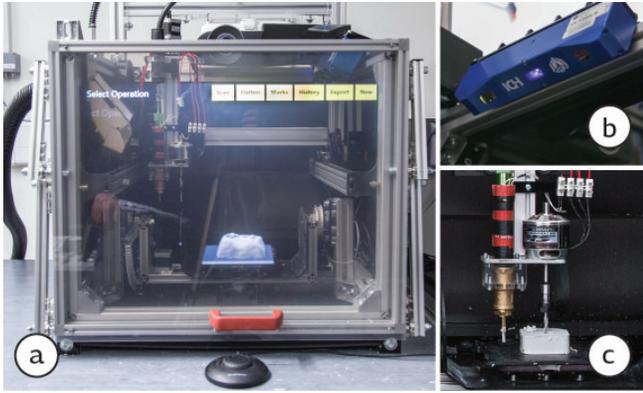


Figure 2. (a) The ReForm prototype system while designing a game controller with the physical object inside the machine and its digital counterpart projected over it. (b) ReForm’s structured light scanner. (c) Additive and subtractive tool head.

Users can then perform ‘on-the-fly’ validation and refinement of the style, size, and confirm each element is fit-for-purpose. Third, the bidirectional mapping between the digital model and physical object facilitates the extension of version tracking from the digital to the physical. Combined with support for both additive and subtractive processes, bidirectional fabrication can extend undo, redo, and add ‘previous version’ functionality to physical objects.

To demonstrate and explore bidirectional fabrication, we built *ReForm* (Figure 2), a system that supports design and fabrication with polymer clay. The ReForm system integrates a custom-built clay 3D printer for additive fabrication, a CNC milling machine for subtractive fabrication, a structured light 3D scanner, and a projected augmented reality display aligned to the physical object. The system can produce shape output by adding or removing clay from an object, and supports recycling of the removed material. It can take shape input from digital 3D models or by scanning physical objects.

The fabrication process starts from either a digital model or a physical object—this can be an existing object or a clay object manually produced by the user. Users provide input by editing the digital model for the next fabrication step, by directly manipulating the shape of the physical object, or by annotating the clay object with markup instructions for the system. The system supports the iterative design process with global operations on the model, such as flattening of the surface, and local operations such as extrusion based on annotation. ReForm keeps track of each model version, allowing users to navigate the design history, undo steps, and have the machine re-shape the object to an earlier version. Fabrication previews overlaying the object and interactive input are provided by a projection-based augmented reality interface.

To summarize, this paper contributes: (1) The concept of *bidirectional fabrication* that enables users to move flexibly between the digital model and physical object in a relaxed turn-taking fashion. (2) ReForm: a bidirectional fabrication system that blends digital modeling and physical shaping practice. (3) A prototype implementation of ReForm and usage examples executed with our implementation. (4) Specific

technical innovations, including the use of a two-state material (machinable and malleable) for interactive design and a novel toolpath generation algorithm for additive and subtractive fabrication.

RELATED WORK

The foundations of bidirectional fabrication; the ability to computationally input and output physical shape are longstanding ideas. In 1965, Sutherland [20] described the Ultimate Display as: “a room within which the computer can control the existence of matter”. Modern interpretations such as Radical Atoms [6] describe *bidirectional synchronization* as key feature of computational materials. Our work stands in this tradition, but adopts external modification in lieu of self-modifying materials.

Interactive and Low-Fi Fabrication

Most systems require the object to be designed in its entirety before it can be fabricated. *Interactive Fabrication* [26] makes fabrication an integral part of the design process. Each design decision is immediately fabricated. This concept has been applied to architecture [19], artistic settings [28] and mechanical devices [11]. ReForm is a form of interactive fabrication, in that design decisions are immediately fabricated. Interactive fabrication in previous instances suffers from material waste as undesired results are discarded—in ReForm, the material can be recycled.

In *Low-Fi Fabrication* [10], the time to fabricate an object is lowered at the cost of accuracy. This enables fast iteration and testing of design choices in the physical world. Low-Fi Fabrication and Bidirectional Fabrication are complementary. The techniques developed in the former can be employed to speed up the model/object synchronization of the latter.

Tangible and Mixed-Reality Modeling

Another approach to digital design is to blend the physical and virtual world. Tangible tools situated in physical space can be used to manipulate virtual models. *ShapeTape* [5] is a deformable strip that can sense its curvature, which can be used to deform shapes. *D-coil* uses a computer-guided wax-extrusion mechanism to create tangible shape proxies [12]. Supporting CAD, *SPATA* [23] integrates active tangible measurement tools (a caliper and protractor) into existing design environments. Construction kits enable users to approximate a desired shape by putting together physical blocks, which once arranged, can sense their configuration [14, 22]. Other systems promote the re-use and mixing of existing arbitrary objects to describe shape [3, 4, 24]. Our system also promotes the use of tangible tools e.g. a ruler or knife to measure and manipulate the object, as well as the re-use of existing artifacts by pressing them into the clay to capture their form.

Augmented reality can be used to overlay digital models onto the physical world, e.g. through head-worn glasses and using tangible geometric primitives for manipulation [8]. *MixFab* [24] enables users to manipulate virtual objects directly with their hands in an augmented reality setup. Existing physical objects can be mixed into the design process, with virtual objects behaving like their physical counterparts (i.e. can be

moved and rotated with the hands). These systems give physical properties to digital entities. ReForm reverses this idea by giving digital properties to physical objects.

Clay-centric User-interfaces

Clay is an intuitive medium for describing shape. Clay-like props have been used as physical proxy for sculpting applications [18] and Piper et al. use clay-based deformable surfaces to build a top-projected landscape analysis system [13]. To sense the shape of a clay-model, Reed embeds locator beacons into the clay [15]. Others explore of clay as in- and output medium. *Digital Clay* [17] considers clay as interaction concept, while *Sculpting by Numbers* [16] is a system for projection guided fabrication of clay-objects from existing 3D models. We draw inspiration from these systems and use clay as a medium for shape input and output.

Toolpath Generation

ReForm combines additive and subtractive fabrication. Both methods are layered and require the generation of milling cutter and material extruder toolpaths. Generating toolpaths for milling operations on a three-axis computer numerically controlled (CNC) machine is a well studied problem [1]. A prominent method is based on isoparametric planar surface curves [9] where a zig-zag curve is sampled and projected onto the model surface to determine the cutting depth. Additive layered manufacturing toolpaths are generated by slicing the model and following the generated profile [7]. In this work, we combine subtractive and additive toolpath generation in one algorithm, based on isoparametric planar curves.

SYSTEM DESIGN FOR BIDIRECTIONAL FABRICATION

ReForm utilizes bidirectional digital fabrication to enable a relaxed turn-taking style of iterative design. By synchronizing the physical object and digital model, the tangible artifact can be altered by users and the system alike. This allows us to maintain important digital operations, such as undoing changes, regardless of their source (user or machine). We also support operations that would be difficult or tedious to perform manually e.g. smoothing clay-modeling artifacts, patterning parts of the model or creating accurate holes. To enable these operations, we build on four key capabilities:

- **Shape Input:** Physical shapes can serve as input. Objects previously produced by ReForm can be input after modification to update their digital counterpart. Other pre-existing objects can serve as starting point for the design process.
- **Shape Output:** ReForm fabricates physical objects which can be inspected, modified, combined, taken into context, compared, used, destroyed and its material reused. These objects need not be completely re-fabricated when the digital model changes, but can gradually be updated by combining additive and subtractive fabrication.
- **Visual Input via Annotation:** Users can annotate the physical objects using colored pens. These annotations are interpreted by ReForm and serve as a selection and command mechanism. As these annotations are made directly on the physical model, they are highly contextual and intuitive to apply.

- **Visual Output via Projected Overlay:** Objects within ReForm can be augmented through projected augmented reality. We overlay information and can enhance the physical object e.g. give new colors, textures or additional information such as the model dimensions or volume. Users can configure operations before they execute, in addition to enabling intuitive visualizations and previews.

An addition, ReForm also supports digital input (via existing modeling environments or online databases) and digital output (via model export). Based on these key capabilities, we provide a variety of operations that can be used to design fabricable artifacts.

Digital Model Management

ReForm maintains and synchronizes a digital model and its physical counterpart. The digital model is a triangle mesh storing geometry, normals and luminosity. On update, ReForm creates a new version of the model, and maintains a copy of the previous version. This version history enables features such as undoing changes and allows new users to understand the steps taken to design an existing object.

The latest model is available to external mesh-modeling systems such as Blender, Maya or Rhino. These systems may alter the digital model; ReForm will then update the physical object. A tight integration into these external software packages (similar to the SPATA tools [23]) would offer a rich set of digital modeling operations, especially for expert users.

Shape Input

ReForm fabricates objects using a clay-like human-deformable material, so that users can manually alter the physical object e.g. with their hands or by using tools (see ‘Physical Shaping’). Once altered, ReForm scans the modified object and synchronizes the digital model. This shape-input mechanism enables users to directly modify the object (hence the model) in physical space. The object can be taken into context, manipulated there and placed back into ReForm for synchronization. Users can add fine artistic details and features that are beyond the shape-output capabilities. Current 3D printers typically produce rigid plastic objects which can not be altered in such a way, thus are less well suited for this iterative design style as alterations have to be performed in the virtual design environment.

Shape Output

ReForm supports physical shape-output, both by fabricating an object from scratch and by incremental updates. This output is performed subtractively and additively, so that the physical object need not be recreated in every update step. Updating, rather than recreating the object offers a range of benefits. First, we do not have to discard the entire physical object for every update. This wastes less material than complete refabrication. Further, users can reuse previously removed material for additive updates, further reducing material waste.

Second, ReForm can choose the fabrication method most suited to a given update or fabrication task. Concave shapes are difficult to produce subtractively, but become feasible additively. Depending on the shape—and in the case of subtractive fabrication, the input material—one method will usually

have a lower fabrication time and each will offer different surface qualities and finishes. We execute shape-output with the most well-suited fabrication method, or when appropriate, combination of methods.

Annotation

Users can directly annotate the physical object using colored marker pens. ReForm detects such annotations during object/model synchronization. Annotations serve two purposes: selection and commands. To select an area for later processing (see ‘Selective Operations’) users draw a closed loop around the area and fill it with a hatch pattern (Figure 4, a).

Visual languages can be used to command machine operations (e.g. Song et al. [19]). In ReForm, a simple annotation language uses drawn shapes to correspond with specific operations e.g. circles with drilling holes, rectangular shapes with surface smoothing and, irregular shapes with extrusions.

Visual Output

To complement shape-output and facilitate interaction, ReForm provides a rich visual output channel comprised of two components: an augmented reality interface and graphical user interface. The augmented reality (AR) interface is aligned with the physical object. We maintain this alignment by correcting for motion parallax, which also provides important depth cues. Through this AR interface we can preview design decisions and new model states before updating the physical model. We use the AR preview to guide users when configuring digital operations such as drilling precise holes or flattening the top surface.

The graphical user interface is overlaid on top of the AR display. Users interact via a jog wheel input device as the UI only necessitates flat menus, sliders, buttons, and sequential selection mechanisms. This form of interaction and UI is in line with existing fabrication machines. As users do not have reach out to the ReForm system (but only hold the jog wheel) we neither introduce fatigue nor occlude the AR interface.

INTERACTIONS AND CAPABILITIES

ReForm combines two previously separate design practices: digital 3D modeling and physical shaping. Users first create a model/object pair, either starting from a digital model or a physical object. Throughout the design process, users manipulate the artifact being designed in a relaxed turn-taking fashion, either through digital modeling operations or by physically shaping it. All operations, no matter if brought about digitally or physically can also be undone.

Model and Object Creation

To begin users must create a digital/physical object pair. Users have the choice to (a) start from an existing digital 3D model or primitive, (b) start from an existing physical object, or (c) to restore from a previous design session/clay representation. If the user does not have a clay representation, ReForm fabricates one. The system recommends a subtractive or additive approach depending on the estimated fabrication time.

Digital models can come from a variety of sources. Online-databases such as Thingiverse¹ and GrabCAD² offer users

¹<http://thingiverse.com>

²<http://grabcad.com>

access to a large variety of existing starting points. Physical objects from various sources can also serve as a starting point. Existing objects, for example items bought in a store, can be used as input and transformed into a model; ReForm can replicate otherwise unmodifiable objects in clay. Users can also start with hand-made clay objects or objects from previous design sessions.

Digital Modeling

ReForm supports a range of operations that makes use of its annotation-input and visual-output features.

Global operations affect the whole model, whereas *selective operations* are applied locally. The latter become selective through annotation-input: users draw on the physical object to mark out the area of influence. Users can manipulate and preview the effect of an operation through the augmented-reality interface, enabling them to make informed decisions.

Besides the operations offered here, existing mesh-based design environments can be used. Users can open and edit the current digital model in e.g. Blender and have ReForm synchronize the physical object.

Global Operations

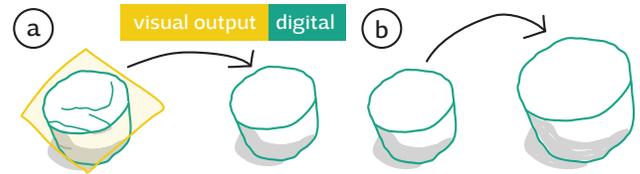


Figure 3. Global Operations. (a) global flatten to produce a level top (b) scaling the whole model

Global operations (e.g. undo, cutting, and scaling) affect the entire model. They are previewed using the visual-output feature before they are applied.

Flatten (Figure 3, a) removes the top of a model to reveal a flat surface. Due to the material properties of the physical object, manual modifications tend to result in undesired artifacts such as waves, ridges and valleys. Using global flatten, users choose a cutting height at which a flat and smooth surface is created, thereby doing away with the undesired artifacts.

Global scaling resizes the model (Figure 3, b) by a variety of measures. Users can scale the model based on a single dimension and scale the others in an aspect-ratio preserving manner, or set the desired value for each dimension individually. A target volume could also be specified, then the object is uniformly scaled to the desired capacity.

Selective Operations

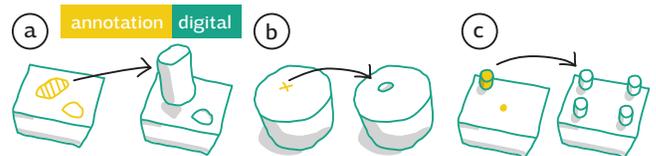


Figure 4. Selective operations using annotations. (a) Extruding an annotated patch or contour (b) Producing accurate holes (c) Patterning model features

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. Through annotations users can also issue commands, selecting the operation to perform. For example, shading in an area offers it for flattening or extrusion (Figure 4, a), drawing a cross results in a hole being drilled (Figure 4, b) and two circles produce a patterning (Figure 4, c).

Local flatten serves the same purpose as its global counterpart: remove undesirable physical manipulation artifacts. Besides annotating the desired flattening area, no further user-interaction is required. The cutting height is automatically determined based on the mean height of the annotated area. Within the annotated area, a smooth surface (with a normal parallel to the average normal of the flattening patch) is created at the determined height.

Extrusion (Figure 4, a) adds depth to the annotated outline resulting in material being removed or added, depending on the extrusion direction. This feature enables users to produce cavities and protrusions which would be difficult or tedious to create manually. Similar to extrusions are holes, which are difficult to produce manually due to varying diameter requirements. A cross annotation marks the center of the hole (Figure 4, b) and users configure the hole diameter and depth through the graphical user-interface.

Replicating patterns is tedious to do manually, but effortless in the digital domain. To create a pattern (Figure 4, c), users select the area they want to replicate, and a reference point using the annotation-input feature. Users can then choose the desired pattern type (circular, rectangular, and linear patterns) on the augmented-reality interface. After choosing the type of pattern, the selected area is replicated accordingly.

Physical Shaping

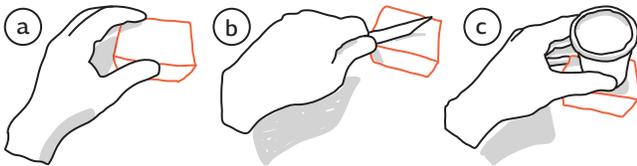


Figure 5. Manual modifications of the material. (a) Users can mold objects with their hands (b) using tools, (c) use existing objects.

Due to ReForm’s malleable material, users can modify the physical objects directly and in context. As the material sticks to itself, users can manually add more material. The shape can also be bent, smeared and otherwise plied using bare hands (Figure 5, a), much like one would with any other clay object. The rich set of existing physical clay sculpting tools can also be used to manipulate the physical object (Figure 5, b). Simple tools like knives and cutters to more specialized sculpting devices provide a broad spectrum of devices, expand the input possibilities for the digital fabrication design process.

Physical objects are not bound to any location, thus can be taken into context and manipulated using any object found in the environment (Figure 5, c). One could create an outline

to serve as guide for other operations by impressing an existing artifact into the clay; for example to create a hole for a pen, users could press the pen into the material. This form of material interaction, combined with the operations detailed below, makes for an intuitive design process.

History and Versioning

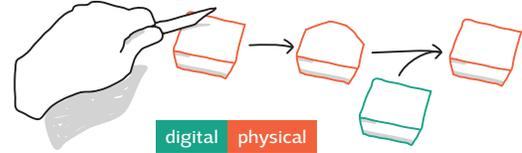


Figure 6. Undoing changes to the model or object. Here, the user modifies the physical object which we can undo using the digital model.

Changes made during the design process can be undone, no matter if the modifications were made on the physical or digital artifact. We maintain a history of 3D models, each of which we can restore as a physical object. This way, we enable free exploration on the physical artifact, as there are no “mistakes” that can be made. Actions that did not result in the desired outcome can be undone. For example, if a user cuts away parts of the object to explore the aesthetics of these changes (Figure 6), but does not consider the outcome desirable, we can restore the previous state undoing the manual interaction. While choosing which version to revert to, ReForm provides a preview using its augmented reality interface.

IMPLEMENTATION

We built a prototype implementation of the ReForm system in order to evaluate the bidirectional fabrication concept. ReForm integrates several components in a novel way: a new material which is machinable, yet malleable; a five-axis CNC machine with a custom clay extruder and milling spindle; a physically aligned augmented reality interface; a structured light 3D scanner; annotation detection and custom toolpath generation to use our machines capabilities.

Material

Common polymer clays and putties are too soft to be machined. Their malleability makes them easy to work with manually and in an additive fabrication setup, but renders them unsuitable for subtractive methods as the soft material clogs the milling bits. To use additive, subtractive, and manual fabrication methods with one material, we use Tec-Clay³ as it is machinable at room temperature but becomes malleable when heated to approximately 50 °C. ReForm can produce both a cool and hot airflow in the machine in order to regulate the model temperature for removing, adding, and forming the material. The extrusion cartridge and nozzle are kept heated to 55 °C to reduce the required extrusion force. At this temperature the clay becomes slightly adhesive and bonds well with itself and the perspex build-platform.

Hardware

We separated the hardware into two main components: the control system (ReForm Core) and the main frame (ReForm).

³<http://www.kolb-technology.com/en/products/classic/clay.html>

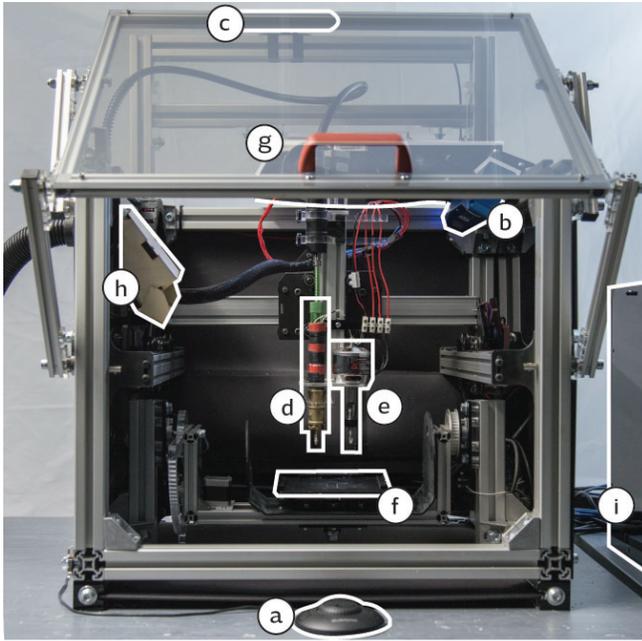


Figure 7. The ReForm prototype: (a) a jog wheel for user-input (b) LMI HDI120 3D scanner (c) Asus Xtion depth camera (d) heated clay extruder (e) milling spindle (f) build plate (g) projector and screen (h) air-guide (i) ReFormCore.

ReForm Core contains supporting components for the main machine. It houses 12V and 24V power supplies, six *CW5405*⁴ 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 ReFormCore cuts the 24V power to the motors if necessary.

ReForm is constructed within an aluminium frame. A spindle drill 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 detents. 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). The airstream is generated using a *Kärcher MV3 P* vacuum cleaner and passed through a heating element. 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 projection screen. In front of the machine (outside of the door) users find the jog wheel (Figure 7, a) for interacting with ReForm.

Spindle and Extruder

The spindle is based on a 260 rpm/V brushless DC motor whose 8 mm shaft we replaced with an ER11 collet (Figure 7, e). A 6 mm flat-tip two-flute cutter is fitted in the collet. Compared with steeper tip angles this flat-tip configura-

tion produces non-clogging clay flakes. The motor speed is controlled from an *Arduino* through an electronic 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 3.1 Nm motor is required. To reduce the moving mass of the XYZ platform we mount the 1.4 kg heavy motor off-axis and transport its rotational movement with a flexible drive shaft to the extruder. This assembly extrudes the clay through a 3 mm heated brass nozzle mounted 2 mm above the cutter (Figure 7, d).

Structured Light Scanner

To 3D scan the object we use an LMI HDI120 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 LMIs *FlexScan* software to align the snapshots and merge them into one 3D mesh model. This scanning process also recovers a monochrome 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 onto the transparent projection screen held in the door. We manually calibrated the virtual camera to match the physical scene, and using an *Xtion* depth camera (Figure 7, c), we track the users body to provide a motion-depth cue. This allows us to render aligned virtual 3D previews over the physical clay model. We use the WPF-based Helix toolkit to render 3D, and custom WPF controls for the 2D menu.

Users interact with the system using a *Contour Design ShuttleXpress* jog wheel (Figure 7, a), which is well suited for the discrete menu scheme and other AR operations. This way the user's hands do not occlude the display, contaminate it with fingerprints, or suffer from fatigue.

System Performance

The toolhead can travel at a maximum speed of 45 mm/sec along the XY axes, 2 mm/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 1 cm³/sec with its cartridge holding 104 cm³ of material. When milling, the maximum spindle plunge depth is 4 mm. The 3D scanner to machine calibration error is less than 0.15 mm.

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 compute 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

⁴<http://cnc4you.co.uk/>

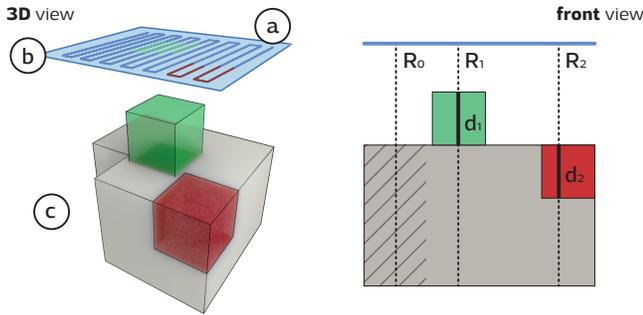


Figure 8. Toolpath generation. (a, b) a space-filling curve is computed on a generator surface within the extremes of the scene. (R_0 , R_1 , R_2) Along the curve, rays are cast normal to the generator surface. (d_1 , d_2) The distance between the existing and target surface determines whether material has to be added or removed.

target surface we want to produce. It consists of four steps: isoparametric curve sampling [9] (see Figure 8), patch extraction, optimization, and path development.

Note that this algorithm does not take the machine geometry into account, and as such might produce toolpaths that result in tool/workpiece collisions (spacing and dimensions of ReForms tools mitigate this problem). This limitation of the algorithm can be addressed by optimizing the generated path so that the workpiece is oriented in a collision free state using the two rotary axis. Near the build-plate and for extreme model convexities no such collision free state exists, thus existing model geometry will have to be removed and rebuilt.

Curve Sampling

We start by constructing an isoparametric zig-zag curve on a generator surface (a plane for XYZ milling, a cylinder for rotary milling), so that the curve fills the extents of the models. We determine the feed-forward step (sampling distance: d) heuristically from the machining tolerance (scallop height: t) and cutter radius r as $d = \sqrt{r^2 - (r - t)^2}$. Even though more advanced estimation methods are available [1], this simple heuristic works well in practice. At each sampled point on the curve we cast a ray normal to the generator surface to determine the machine action required at this point (see Figure 8, right). Three cases are possible:

1. **No intersection** (R_0): the cast ray intersects neither the existing nor the target surface. No action is required.
2. **Target Surface before Existing Surface** (R_1): the ray intersects the target surface before the existing one, hence material needs to be added.
3. **Existing Surface before Target Surface** (R_2): the ray intersects the existing surface before the target one, hence material needs to be removed.

Patch Extraction

The previous step produces a path consisting of subtractive, additive and passive samples (Figure 8). We group consecutive samples of the same kind forming *machining patches*. Passive patches (see case 1 above) become travel moves along

the path. At this point we decide whether we want a subtractive or additive path and replace the other patches with travel moves also.

Optimization

We now have the surface machining path with many unnecessary travel moves. We optimize travel patches by finding the shortest path between the start and end point of the patch along the generator surface. The travel height is determined by sampling the existing model along the new travel path via ray casting.

Path Development

The optimized surface machining path does not account for material being successively taken away or added. In this step we interpolate the path remove to material at a given layer height (and not plunge all the way into the model), or add material at that height respectively. In this stage we also incorporate fabrication specific aspects, such as a slower first layer when adding material, to ensure it bonds well with the printing surface.

Implementation Details

Our algorithm relies heavily on ray-casting meshes. We accelerate this process using a KD-tree to reduce the required triangle-ray intersection tests. Sampling a 100×100 mm planar zig-zag curve with a $t = 0.5$ mm machining tolerance and $r = 1.5$ mm cutter radius (resulting in a sampling distance of $d = 1.118$ mm) requires 7921 ray-casts.

Using spherecasts (mesh-sphere intersection along a ray), rather than raycasts would yield toolpaths closer resembling the model surface. However, spherecasts come at a computational and simplicity-of-implementation expense.

Annotation recognition

We use the *DBSCAN* clustering algorithm [2] to detect user-drawn annotations on the model. First, we compute a set of candidate vertices by applying a Luma threshold filter on the monochrome vertex colors recovered by the 3D scan. Then we cluster vertices based on their color and spatial proximity using *DBSCAN*. To ensure the cluster is on the surface, we check if all vertices in the cluster are topologically connected in the mesh.

To detect shapes (e.g. unfilled rectangles or crosses), we fit a plane into the cluster vertices, project the vertices onto that plane and compute their convex hull. We then find all connected vertices which projection falls in the convex hull using an arbitrary vertex in the cluster as seed point. As a result we get all vertices within the cluster—no matter if they were colored or not—and a 2D projected image that we can use to detect commands.

APPLICATION EXAMPLES

We describe two application examples to demonstrate ReForm's features and benefits. Both examples highlight how ReForm blends digital modeling with physical shaping and demonstrate turn-taking in the bidirectional fabrication process. The first illustrates a single-user design that combines



Figure 9. Objects designed with ReForm. (a) User wearing the exported smartwatch prototype. (b) 3D printed and clay versions of the game-controller. (c) Key hook. (d) Phone dock and corresponding clay object.

shape input from physical ‘on-body’ sculpting with annotations to support the precise insertion of electronic components. The second describes a group-based design of a game-controller that starts with a physically sculpted base-shape and evolves, via multiple turns and iterations, to a 3D-printed artifact. Both demonstrate physical history.

Walkthrough: Smartwatch

In this example we use ReForm to construct a smartwatch prototype that we mold to fit a users wrist, yet precisely hold electronic components. This demonstrates how organic physical shaping and precise digital manipulation are combined in bidirectional fabrication.

We start by creating the body of the watch by manually cutting a block of clay. After warming the clay it becomes malleable and we can shape the watch body. During this process we can try the prototype on our wrist to see if it fits as a watch and will be comfortable to wear. When the rough shape is complete, we place the object on a build-plate, insert it into ReForm and create a new model by scanning the clay object.

After ReForm scanned the model, we use the *global flatten* operation (Figure 10a) to smooth the top surface of the watch. Once we confirm the desired cutting height, ReForm updates the digital model, and its physical counterpart (Figure 10b).

Next we need to make space for the display and electronics. To this end we use the display and physically press it into the soft clay (Figure 10c). With a marker, we then mark the created impression (Figure 10d) to select the area which we want to carve out. The object is re-inserted into ReForm and scanned. ReForm detects the annotations and offers the *selective extrusion* feature (Figure 10e) which we use to create the display cavity. Once confirmed, ReForm updates the physical object and carves out the material as designed (Figure 10f).

We take out the updated object, place the display inside the cavity and try the prototype on our wrist. With the compo-

nents placed as desired, we finalize the watch design by shaping the watch body (Figure 10g). Using sculpting tools we directly manipulate the physical clay object.

Once all components are placed and the shape of the smart-watch is as desired, we can take the so created digital model (Figure 10h) and 3D print it in a more suitable material i.e. PLA. This produces the final prototype which is subsequently assembled and used (Figure 9a).

Walkthrough: Game Controller

In this example we develop a new game controller and experiment with different designs and button configurations. Here, we demonstrate how ReForm can be used in a collaborative setting where multiple users can make changes to the design by modifying the physical object in-turn.

Using existing controllers as a guide, we begin with selecting a block of clay from which we form the basic shape of the controller. We use our hands to approximate the curvature and geometry of the design (Figure 10i); creating a depression in the center and sides which follows the crease of the hands. Using tools we carve away chunks of clay. Where we remove clay accidentally, or make changes feel wrong, we push the clay back into place. This process is repeated until we are happy with the base shape.

Next, the controller is placed into the machine. We select ‘Create From Scan’ to start a new ReForm session using this object. Once the scan is complete, we select the ‘Flatten’ command to create a flush working surface. Using the augmented-reality preview we locate a cut height that will leave no troughs on the surface before confirming the operation. No measuring is required. The digital model (thus the physical object) is then flattened and updated accordingly.

Once complete, we take the clay out of the machine and place it amongst a set of available interface components. Everyone in the group holds the prototype, passes it around, and alters the button placement (Figure 10j); discussing the merits of alternatives—a person with smaller hands uses a fingernail to score a line in the clay that illustrates their constraints. A three-button configuration is agreed and the final button positions are marked out with a pen (Figure 10k). The annotated clay is placed back into the machine, which after scanning, detects the marks. We select each the mark and instruct the machine to extrude to the specified height and radius.

We then remove the object from the machine and add a directional-pad to the right-hand-side of the model. A few people try the design to ensure the pad can comfortably be reached. During this process, we accidentally smudge out a button (Figure 10l). To fix this, we place the object back in the machine (Figure 10m) and select the previous, undamaged version. This causes the machine to perform a local milling operation to clear away the damage, followed by extrusion to replace the button (Figure 10n).

Lastly, we take the repaired model from the machine and draw a pen line around the edge of the shape to describe a lip. Back in the machine, the drawn path is detected and extruded down 2 mm. We then select ‘export’ and send the finished

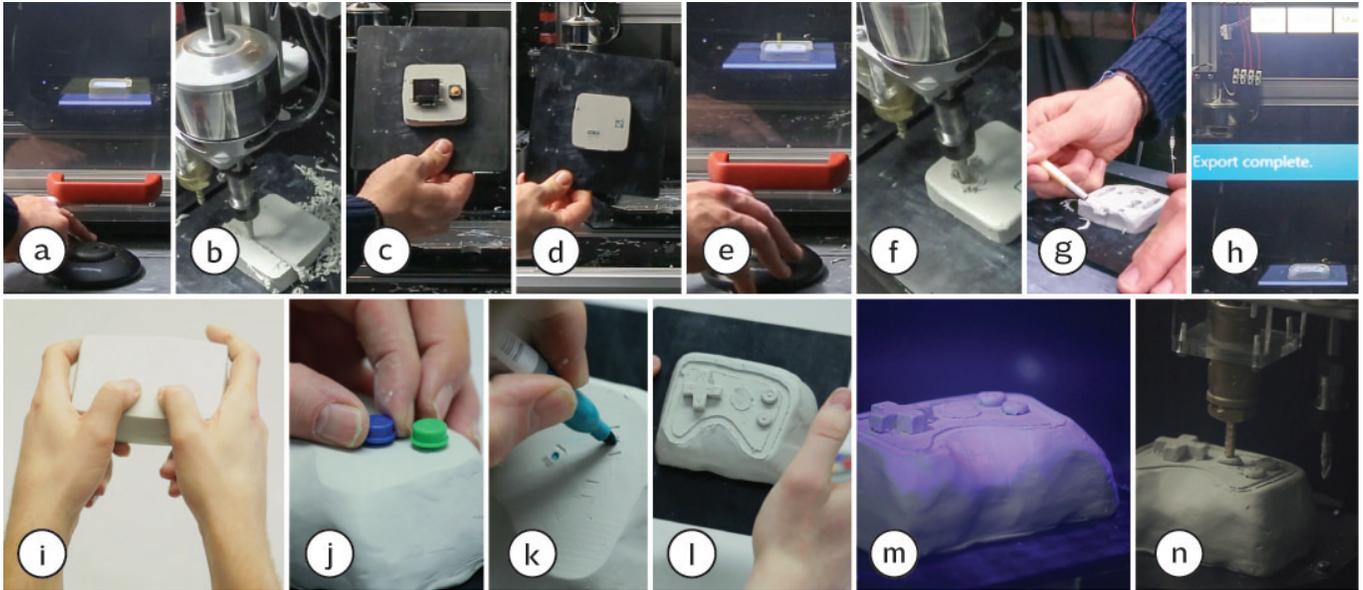


Figure 10. ReForm design walkthrough: (a) flattening the top surface (b) ReForm updating the physical object (c) existing components placed on the prototype (d) component positions are annotated (e) using selective extrusion to create the display cavity (f) the physical object is updated (g) the user shapes the watch to their liking (h) a final model is exported for 3D printing. (i) shaping a game controller (j) placing buttons on the prototype (k) annotating the button positions (l) user damaged the prototype (m) damaged object is scanned (n) ReForm repairs the object.

model to a 3D printer for fabrication (Figure 9a). The clay prototype is recycled.

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 can not be modified. To do away with the buildplate, one could use the Iterative-Closest Point algorithm [27] or apply infrared registration markers to the model e.g. spraying a random 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 prototype 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 scan the object after each physical update and update the digital model accordingly. This can lead to an accumulative error, thus make the model 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 addition 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 curvature sensors 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

design system that blends digital modeling and physical shaping practice. We have implemented a ReForm prototype and shown application examples, demonstrating the novel interactions and benefits offered by our system.

In lieu of computationally bidirectional materials, we have implemented external modification of objects. ReForm shows how bidirectional fabrication can be applied today, allowing researchers to explore interactions with such materials.

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