

FabSquare: Fabricating Photopolymer Objects by Mold 3D Printing and UV Curing

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Rapid prototyping tools provide practical methods for personal fabrication, allowing designers and engineers to refine and iterate their ideas quickly. Because of their low cost and versatility, 3D printers in particular are becoming increasingly popular. Although 3D printers are incredibly powerful devices for creating complex geometries, they are inherently slow and only print materials that are within a small range of properties. This puts them in clear contrast with classic fabrication processes such as injection molding, where speed and high throughput come at the expense of cost and flexibility.

The FabSquare system fabricates objects by casting photopolymers inside a 3D printed mold. The molds are printed with UV-transparent materials to allow for UV photopolymerization. Because it uses simple and inexpensive hardware, FabSquare is suitable for ordinary users in nonspecialized labs.

Injection molding is the process of injecting molten thermoplastic materials into a mold cavity, inside which they harden as they cool. The conventional mold-making stage is painstaking, expensive, and slow. Apart from the mold development, the required machinery is also prohibitively expensive and best suited for producing thousands to millions of parts.

To address these challenges, we developed *FabSquare*, a system that brings injection molding into the realm of personal fabrication by leveraging 3D printing and interactive design. The FabSquare system is similar to injection molding, except that it works with photopolymers and the solidification

of the mold content is carried out by ultraviolet (UV) energy. We replace the expensive and time-consuming mold-making stage in injection molding with 3D printing and substitute the high-pressure, high-temperature process involving large and costly hardware with simple injection and UV curing.

Recently, 3D printing has been used as a tool to fabricate molds for traditional thermoplastic injection molding. The molds are temporary and used to test mold geometries and for short production runs. Typically, the molds only last for several dozen injections because the mold polymer degrades under high pressure and heat. Moreover, such molds still require the heavy machinery used for injection molding. UV injection molding has also been used at the μm and mm scales. In biology, UV microinjection molding allows for fabricating biocompatible hydrogel structures¹ and biosensors.² Micro UV molding has been used to fabricate micro-optical devices.³ While, to the best of our knowledge, there is no literature on the fabrication of large-scale objects via 3D printing combined with UV injection molding, we believe that the main contribution of our work is to introduce a flexible fabrication method that is suitable for researchers without access to complicated hardware, such as computer graphics researchers. (See the “Related Work in Casting and Personal Fabrication” sidebar for more details about previous work.)

Compared with injection molding, FabSquare is significantly less expensive and less complicated, with much simpler hardware requirements, and

Related Work in Casting and Personal Fabrication

Injection molding is one of the most popular methods for manufacturing plastic parts¹ because it is capable of fabricating relatively complex parts with high accuracy. In this method, raw materials melted under high temperature and high pressure are fed into a mold and then hardened via cooling. Figure A shows a simplified diagram that illustrates the injection molding process. Injection molding requires high startup costs and long lead times before the first part is produced.² The metal mold is expensive—on the order of tens of thousands of dollars—and takes weeks to draft, design, and manufacture. This approach is best suited for the mass production of end-use products.

Personal fabrication devices, such as 3D printers and laser cutters, are versatile tools for producing single-item parts.³ Numerous recent works have been focused on speeding up various personal fabrication processes. For example, parallelizing multiple heads can significantly increase the printing speed.⁴ WirePrint fabricates low-fidelity previews of a prototype by printing a wireframe mesh.⁵ faBrickation limits 3D printing to the parts of the object where a higher resolution is needed, and the user puts Lego-like bricks everywhere else.⁶ CofiFab is a computational method that fabricates highly detailed, large-scale objects rapidly.⁷ It fabricates the interior shell with a laser cutter and 3D prints the outer surface.

There have also been recent efforts to create custom thermoforming setups for generating one-off, textured objects.^{8,9} Like FabSquare, one of these approaches uses molds to cast the object made of gypsum.⁸ However, in that approach, the mold is destroyed when the object is removed.

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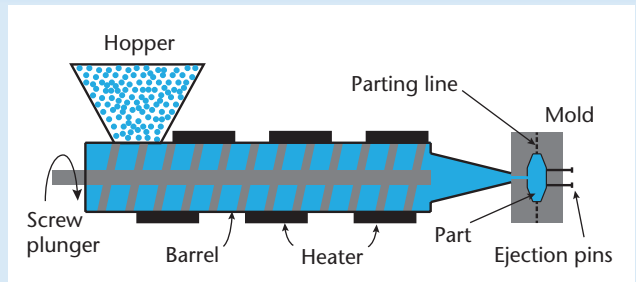


Figure A. Simple demonstration of the injection-molding process. The material is fed from the hopper into the barrel and forced by the rotating screw plunger into the mold cavity. The heaters melt the material and keep them molten. After cooling and hardening inside the mold cavity, the part is released with the help of ejection pins.

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is therefore within the reach of ordinary users. Compared with 3D printing, the printed mold in FabSquare can be reused to rapidly create additional copies of the intended object. Hence, it is well suited to situations where more than a handful of parts are needed. Moreover, many different additive components can be mixed with the photopolymer to improve its physical properties. This is an important advantage over 3D printing, which only works with a limited range of material properties. FabSquare does have some limitations: Similar to injection molding, the maximum achievable thickness with UV curing is limited. Moreover, the FabSquare editor does not support molds with more than two parts.

FabSquare Workflow and Technical Details

To fabricate a CAD model, the FabSquare workflow follows these steps:

1. Design a mold geometry.
2. Fabricate the mold with a 3D printer.
3. Fill the mold with a specified polymer material.
4. Solidify the fluid inside the mold with UV-triggered polymerization.

Figure 1 and an online web extra video (see <https://youtu.be/a-s13U5uLAE>) illustrate each of these four steps. First, the user specifies the geometry in the form of a digital model. The mold can

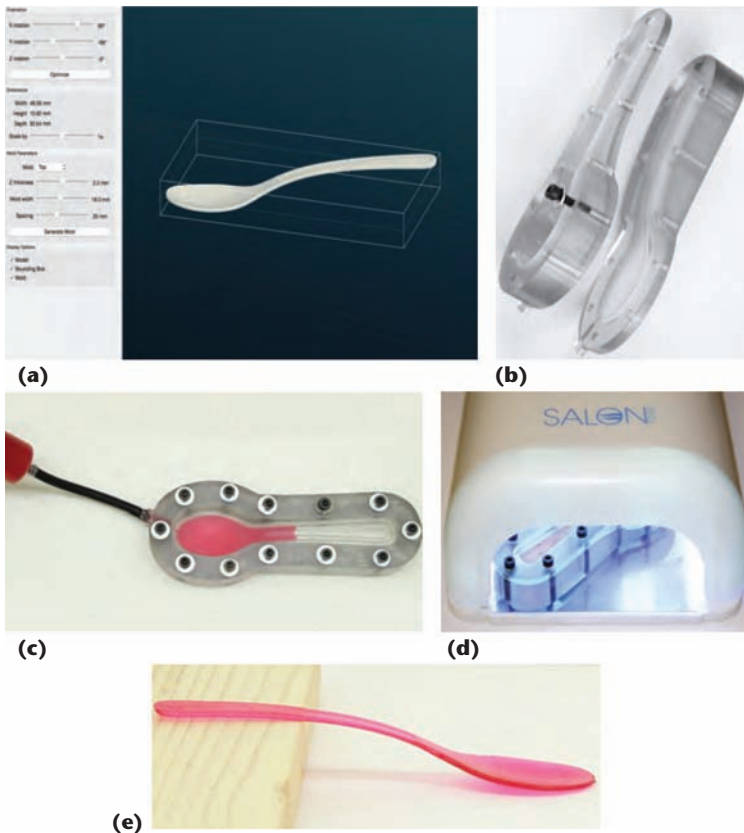


Figure 1. The FabSquare workflow. To fabricate a CAD model, the FabSquare workflow follows these steps: (a) design a mold geometry, (b) fabricate the mold with a 3D printer, (c) fill the mold with a specified polymer material, (d) solidify the fluid inside the mold with UV-triggered polymerization, and (e) remove the object from the mold.



Figure 2. Example objects fabricated with FabSquare. From left to right, clockwise, we can see a propeller with phosphorescent pigments, a hook with silica particles, a spoon with colored pigment, a carbon fiber wrench with an embedded RFID tag, and a second wrench mechanically reinforced with clay particles.

then be designed from the model in a 3D CAD software. The output is two STL files that can be directly printed with UV-transparent materials. Next, the photopolymer fluid is injected into the tightly clamped mold. Then, the mold containing the material is exposed to UV light, and the polymerization takes place. After the liquid inside the mold solidifies, the object can be removed from the mold.

Figure 2 shows a set of example objects created with FabSquare.

Mold Design

The mold’s digital design can take place in a CAD environment, such as SolidWorks. We have also developed a stand-alone application that performs the same design steps with a high degree of automation. (We describe our mold-design application in detail later in this article.)

The intended 3D geometry for fabrication is used to generate two halves of a mold: A side and B side. The design includes a material inlet and an air outlet in order to let materials flow through the mold. We should be able to tightly clamp the two halves of the mold together in order to prevent the material from leaking out of the model region. For this, we distribute screw holes along the mold’s periphery evenly and densely. Figure 3a shows the outline of a designed mold after printing.

The maximum mold outline surface area is limited by the area of the 3D printer’s tray and the size of the UV-curing module. The part’s maximum thickness is limited by the maximum thickness of material that can be uniformly cured.

3D Mold Printing

To print the molds, we used an Objet Connex 260, a multimaterial 3D printer that uses phase-change photopolymer-based inkjet technology. We also experimented with a less-expensive fused deposition modeling (FDM) printer with UV-transparent filaments. The Objet printer supports a variety of polymer-based materials that vary in color, elasticity, and optical qualities. We used Objet VeroClear, a material that has high transparency in the UV range of light. The device software takes per-material geometry meshes as an input.

The shield around the mold cavity should be designed so it is thin enough to let the UV light pass through it efficiently. The other parts of the mold should be optically thick against UV illumination. This can be achieved by thickening the nonmodel parts of the mold when printing with a single, transparent material. Alternatively, we can use a multimaterial mold in which a second material

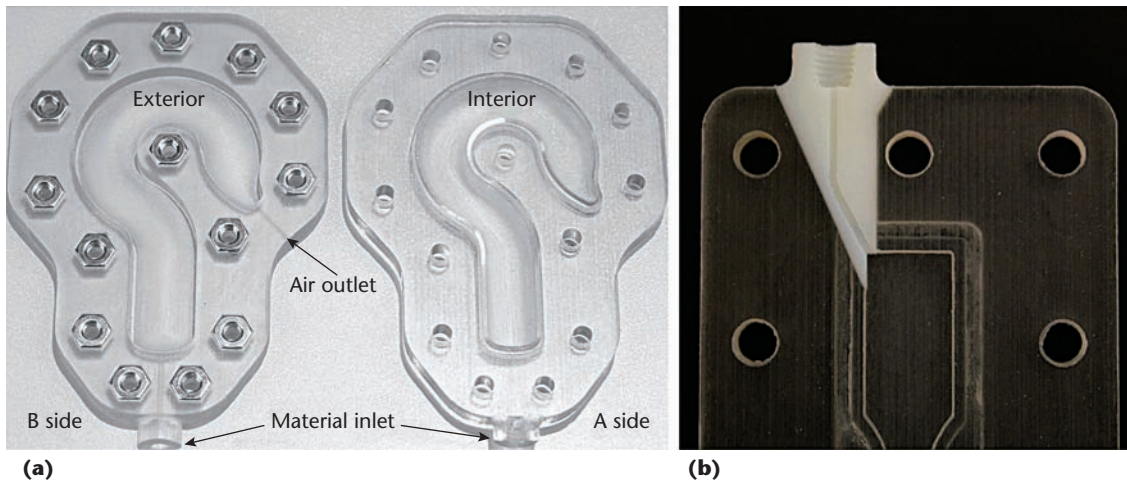


Figure 3. Mold design: (a) a 3D printed mold for fabricating a hook and (b) a multimaterial mold. The material inlet is printed with an opaque material (Objet Endur). This image shows the interior of one side of the mold.

blocks the UV light in the sensitive parts of the mold, such as the material inlet (see Figure 3b). This prevents the polymerization of materials that might remain in these areas. Such design facilitates the post-curing separation of the two halves of the mold and lengthens the mold's lifetime.

We can have two different surface finishes for the interior of our molds printed with the inkjet printer: glossy and matte. For the matte finish, the printer deposits a few layers of support material, thereby roughening the mold interior's surface. In the absence of the release coating, the level of micro-roughness in the mold could affect the cast surface and change its gloss. However, without release coating, it becomes difficult to separate the mold and the cast. Figure 3a shows the two sides of a printed mold. The screw holes are on the A side and places for nuts are on the B side.

UV Curing

UV curing, also called *photopolymerization*, is a set of complex chemical reactions that lead to the solidification of a fluid.⁴ The UV curing for this process can take place under any UV light that provides uniform illumination on the model. The filled mold is exposed to the UV light, which triggers the polymerization and solidifies the mold's content.

In our experiments, we used a nail UV lamp (which cost approximately \$20) for curing (see Figure 1d). However, for faster curing, a UV unit with higher power is more desirable. For the majority of the fabricated parts, we used an F300S UV curing unit from Heraeus Noblelight Fusion UV. It has a radiant exposure of 15 W/cm² with a broadband spectral curve peaked at 390 nm. The UV unit is coupled with a moving conveyor belt, which allows us to control the speed and therefore the duration of curing. After curing, the screws are removed and the two parts of the mold are separated from the object. To ease the separa-

tion, we apply a release coating to the mold's interior surface.

Material Library

All the base materials we used are based on UV-curable photopolymers. These materials are readily available, but we used a custom formulation previously formulated for an inkjet 3D printer.⁵ The raw material is a mixture of three kinds of monomers and oligomers, plus 2 percent photoinitiator (Irgacure 819 from BASF) that initiates polymerization when exposed to UV light. We used two formulations for our photopolymers. The first one, called RIG, results in an optically clear, mechanically rigid object with a subtle yellow tint. The second one, called ELA, results in a clear elastic polymer.

Additive Components

An interesting feature of FabSquare is that it allows us to add new components to the base photopolymer. Compared with similar 3D printing technologies, such as phase-change inkjet, FabSquare does not require careful control of the material's rheology. In inkjet printing, the printhead works within a relatively narrow range of material viscosity. FabSquare is largely independent of viscosity—the only requirement is that the fluid can be injected into the mold.

Another important limiting factor when working with 3D inkjet printers, such as the Objet Connex, is the particle size of additive materials. The particle size should be sufficiently smaller than the diameter of the printhead nozzles to prevent clogging. FabSquare is not affected by this limitation because the material inlet can be as wide as practically necessary.

Yet another issue is that similar printing technologies need a homogeneous suspension of additives in the base photopolymer. Because the fabrication can take hours, there is a possibility that the additives will segregate from the base photopolymer.

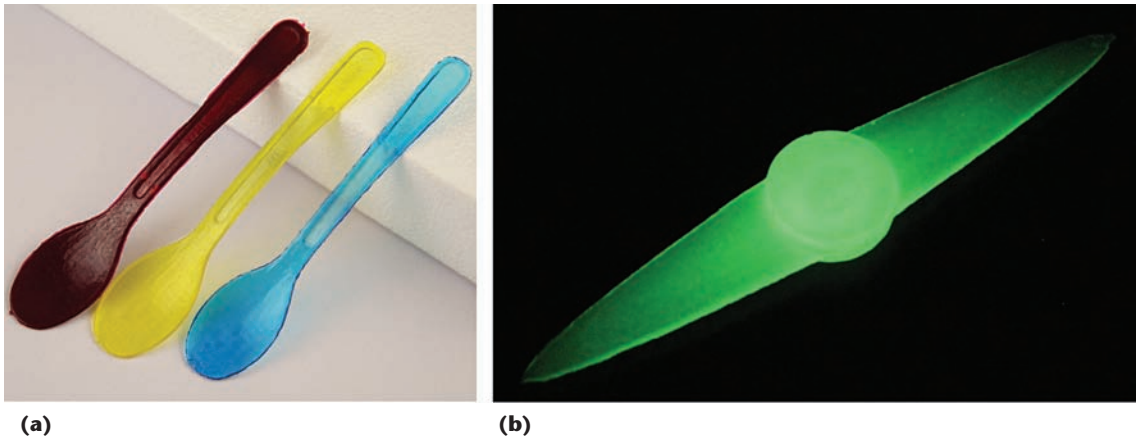


Figure 4. Color and phosphorescent pigments. (a) The spoons were fabricated with RIG photopolymer and colored with different color pigments (purchased from RJA Dispersions). From left to right, we used 4.0, 0.08, and 0.08 percent of magenta, yellow, and cyan pigments, respectively. (b) The phosphorescent propeller (shown in a dark room) was fabricated with RIG photopolymer and 3.0 percent green phosphorescent pigment (purchased from GloEffex).

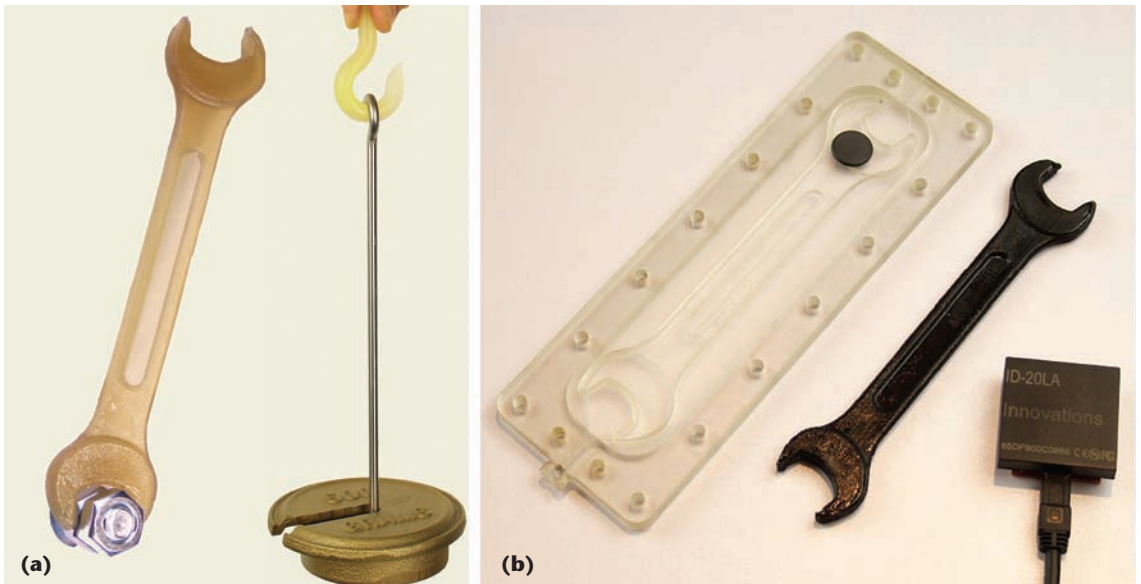


Figure 5. Mechanical additives. (a) This image shows a hook with 2.0 percent nano-silica particles and a wrench with 4.0 percent nano-clay, mixed in RIG photopolymer. (b) With an embedded RFID tag, the smart wrench can be identified using an RFID reader. We also added 2.0 percent carbon fiber to the base RIG material to reinforce the wrench.

FabSquare is not sensitive to slight inhomogeneities in the material because the material feeding is instant; no extra care is needed to keep the material homogeneous during the fabrication.

Color pigments can be added to the base photopolymer to fabricate parts with different colors. The final appearance depends on the pigment concentration and the part's thickness. Figure 4a shows the same geometry colored with different pigments. The opacity increases by increasing the color pigment concentration and/or the part thickness. We might also employ a white pigment mixed with color pigments to tune the opacity.

Phosphorescent pigments are molecules that can be excited, typically with UV light, and that release energy over the time. They create appealing visual effects when charged and then observed in a dark environment. Depending on the type of molecules, they can glow with different colors and for different durations. Figure 4b shows a part fabricated with our RIG photopolymer loaded with phosphorescent additives.

Traditional components, such as clay and silica particles, enhance the mechanical properties of photopolymers.⁶ We can add *mechanical additives*, specifically nano-clay (purchased from Nanocor)

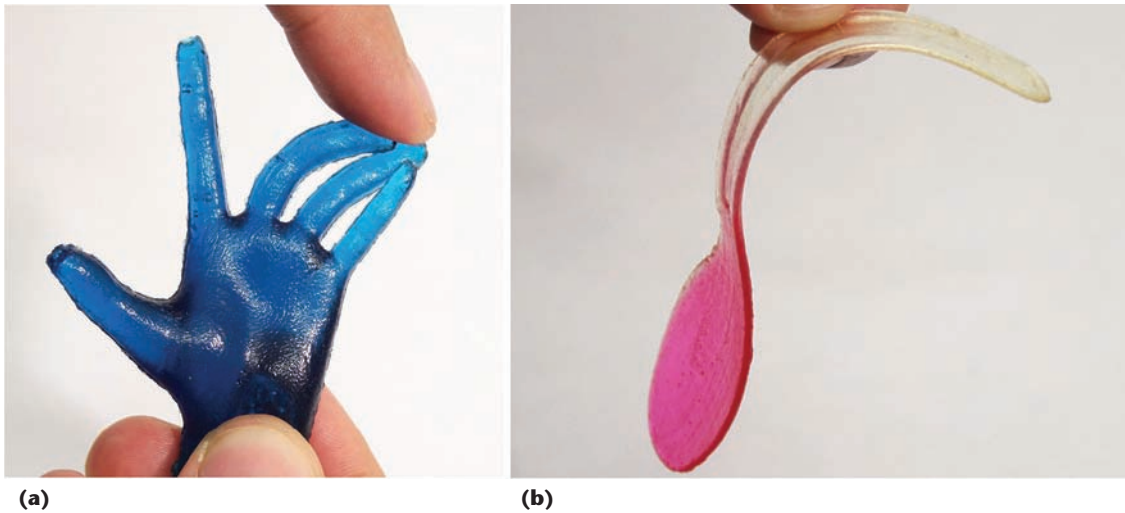


Figure 6. Alternate-material formulations: (a) an elastic hand model with 0.01 percent cyan pigment and (b) a multimaterial part made of rigid (colored with magenta pigment) and elastic materials.

and nano-silica (purchased from US-Nano), into our photopolymer base to enhance the mechanical properties of our fabricated objects. Figure 5a shows parts made of RIG polymer that have been mechanically improved by adding silica particles and nano-clays to the photopolymer.

We can also add carbon fiber (purchased from Zoltek) to the photopolymers prior to curing. Although some research prototype printers fabricate enforced polymers with carbon fibers,⁷ inkjet printing is not appropriate for this purpose because the preferred length of carbon fibers is at least 200 microns. Figure 5b shows an enforced wrench loaded with 2.0 percent carbon fiber.

Radio-frequency identification (RFID) tags can be embedded in our photopolymer objects and be tracked using an RFID reader. This is an example of personal fabrication of smart objects. Figure 5b shows an object that can be identified thanks to the RFID tag inside it. Before filling the mold, we place the tag inside the wrench. Because the mold's temperature during UV curing raises moderately, the RFID tag remains functional. We tested the same tag by putting it inside a furnace at 220°C, a temperature common to injection molding. Because of the high temperature, the tag fails to be detected by the reader.

Alternate Formulations

In the previous sections, we described rigid formulations for part fabrication. We can also use a second formulation that results in an elastic polymer. The FabSquare workflow is the same for both formulations. Figure 6a shows a hand model fabricated with ELA photopolymer and colored with the cyan pigment.

Interestingly, we are also able to make a single object with different materials juxtaposed. Using our current settings, we injected different materials with the help of a manifold connected to the material inlet. Designing a system capable of controlling the distribution of different materials is an interesting avenue of future research. Figure 6b shows a spoon that has a rigid bowl and an elastic handle.

Less Expensive Setups

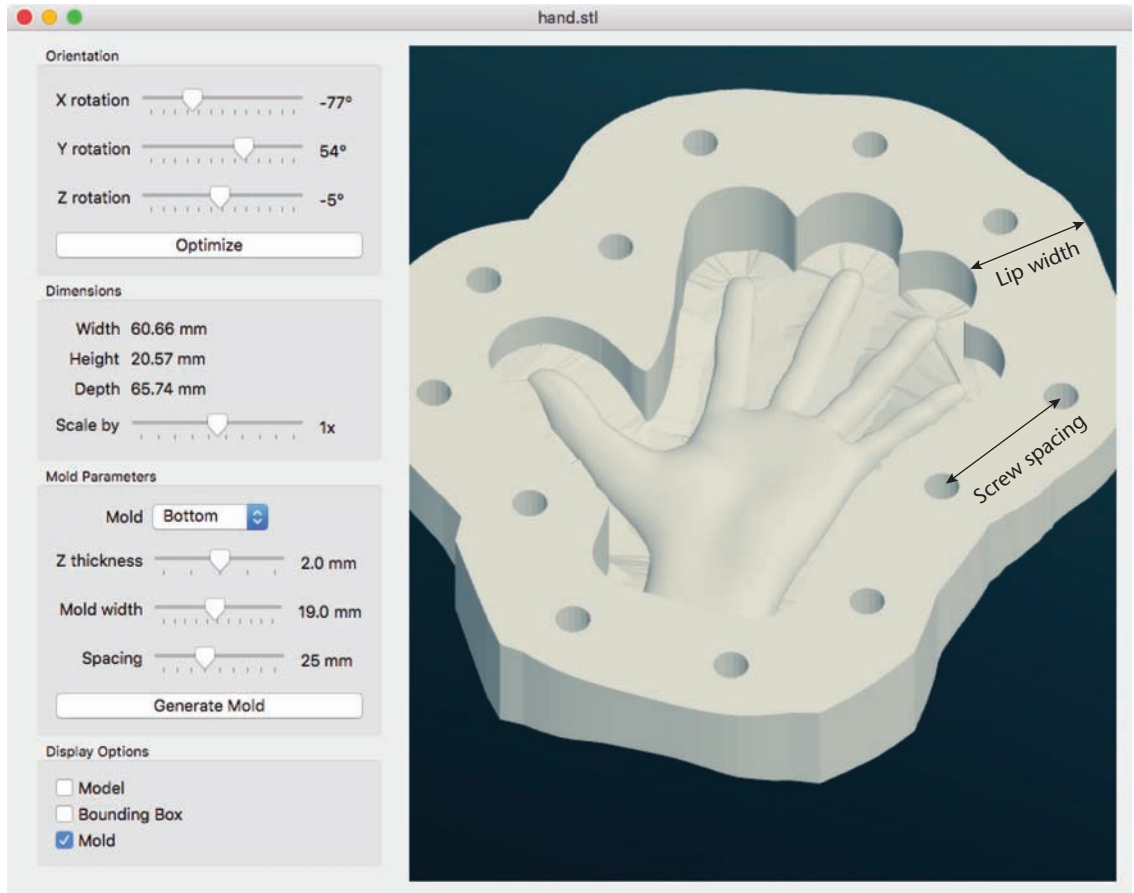
As we mentioned earlier, we successfully used a nail UV lamp to fabricate objects inside molds printed with the Objet printer. One example is the elastic hand model in Figure 6a. The curing however is much slower than under a powerful enough UV unit (about 10 minutes instead of 20 seconds).

To test different setups, we performed a set of experiments using a less expensive printer. We printed the hook mold with a Zortrax M200 FDM



Figure 7. A mechanical hook colored with cyan pigment. The mold (right) is printed with an FDM printer using a clear filament.

Figure 8. FabSquare Editor. Using a graphical interface, users can load an input STL file, scale and rotate the mesh, and specify various parameters. The software then automatically generates STL files corresponding to the two halves of the mold, ready for 3D printing.



printer, which costs approximately \$2,000 (Figure 7). In this case, the nail UV lamp did not totally cure the sample because the clear filaments are not transparent enough, especially after printing. For the FDM mold, we carried out the UV curing using our more powerful Fusion UV light source.

One alternate solution would be to use an SLA printer, which is inexpensive (about \$3,000) but has materials similar to polymers in inkjet systems.

FabSquare Editor

We build the FabSquare Editor to simplify the mold-generation process for users without much technical expertise. Via a graphical interface, users can load an input STL file, scale and rotate the mesh, and specify various parameters. The software automatically generates STL files corresponding to the two halves of the mold, ready for 3D printing. Figure 8 shows a screenshot of the FabSquare Editor's user interface.

Orientation and Scaling

The FabSquare Editor lets users manually change a mold's orientation by specifying rotations along the x , y , and z axes; the model is rotated into the new orientation such that the two halves of the mold lie in the positive and negative z direction. There is also an optimize option that identifies the orien-

tation that maximizes the mold surface area that will be exposed to UV light, which helps achieve a higher curing depth.

We measure the area of the mesh projection onto the x - y plane by adding up the areas of all constituent triangles after projecting them onto the x - y plane. The program maximizes this area by treating the area function as a black box and running a generic numeric maximization over x , y , and z rotation; this computation is independent of the shield's z thickness.

A scale slider also lets users linearly scale the model up and down to a size best suited for fabrication.

Mold Generation

The FabSquare Editor assists the user with several mold generation parameters: the shield's thickness above the mold cavity, the width of the lip around the mold, and the spacing between the screw holes. We set the default options to values we found to work well in practice: 2.0 mm shield thickness, 19 mm lip width, and 25 mm spacing around the mold.

Before generating the mold, the software first checks for overhangs in the model by tracing rays through each facet of the mesh in the z direction and counting the number of intersections. An overhang would correspond to a ray that intersects the mesh more than two times. Overhangs prevent

two-part molds from separating and releasing the model cleanly after curing, so the software alerts the user if it finds any.

Next, the FabSquare Editor calculates the cutting contour—that is, the contour around the model where the two halves of the mold meet. If there are no overhangs, a cutting contour exists that will yield a mold that can separate cleanly. For many surfaces, the cutting contour will not be a planar curve. An edge will lie on the contour if and only if its two adjacent edges face up and down—that is, if the dot product of two face normals with the z axis give opposite signs. Because the cutting contour is continuous, we can iterate through these edges and order them into a clockwise contour around the mesh’s exterior.

This contour is then projected down onto the x - y plane and expanded outward to yield the mold’s 2D outline. The software then fills in the outline via constrained Delaunay triangulation, extrudes it to form a prism, and subtracts away the original model to obtain *outerMold*, the mold’s basic geometry. We then repeat this process with a smaller expansion coefficient and shorter extrusion height to obtain a smaller copy of the mold, *innerMold*. By subtracting *innerMold* from *outerMold*, the FabSquare Editor creates the thin shield necessary for effective UV curing. Finally, the screw holes for clamping the two halves together are created using more mesh subtraction operations.

Pseudocode describing this process in greater detail is available in online supplementary materials at <https://extras.computer.org/extra/mcg2017030034s2.pdf>. The optimize operation that finds the mold’s best orientation takes no more than five seconds, even for large meshes. The slower mold-generation process requires 43 and 104 seconds for a spoon (13,026 triangles) and a propeller (17,664 triangles), respectively, using a 2-GHz Intel Core i7 processor and 8 Gbytes of RAM.

External Dependencies

Our implementation relies on *fstl* for fast STL manipulation, *Clipper* for 2D polygonal offsetting, *libIGL* for robust mesh Boolean operations, *CGAL* (Computational Geometry Algorithms Library) for constrained Delaunay triangulation, and the GNU Scientific Library for numerical optimization.

Evaluation

To demonstrate the potential of the proposed FabSquare method, we fabricated several objects with different properties. These result show that this technique can be useful for computer graphics

Table 1. Maximum cured thickness of different material compositions under 15 seconds of full-intensity UV illumination.

Material composition	Max cured thickness (mm)
ELA	24
RIG	23
RIG + 0.08% yellow pigment	13
RIG + 0.08% cyan pigment	19
RIG + 3.0% phosphorescent pigment	23
RIG + 4.0% clay particle	20
RIG + 2.0% silica particle	18
RIG + 2.0% carbon fiber	11

and computational fabrication communities because it allows them to fabricate a range of objects affordably and rapidly.

Fabrication Time

Because we automated the mold-design process, the most time-consuming step in FabSquare is the mold printing. The printing time depends on the mold size and geometry. Larger shapes, especially those with more layers in the z axis, are slower to print. This is a one-time requirement, however, because the molds can be used for many fabrication cycles.

The remaining fabrication time in FabSquare is spent on coating the mold interior, injecting the material, closing the mold with screws, UV curing, and opening and cleaning the mold. These steps usually take less than 20 minutes, regardless of the object’s size.

Maximum Curable Thickness

An important parameter in photopolymerization is the maximum thickness that can be cured. This parameter depends on many factors, such as photopolymer formulation, photoinitiator, and additives.⁸


In a simple experiment similar to the ISO 4049 standard,⁹ we filled a printed container with different compounds and exposed it to UV light under the UV Fusion unit for 15 seconds. Table 1 lists the total cured thickness (the sum of cured depth, from top and bottom). As we can see, some additives prevent the polymerization, whereas others have a less inhibitory effect. The curable thickness in FabSquare is similar to the maximum thickness achievable with traditional injection molding. The minimum feature size achievable with FabSquare, however, directly depends on the printer’s ability to manufacture smaller cavities.

Mold Lifespan

The main factor limiting a mold’s lifespan is the polymer glued to the mold after curing. This is

more serious in sensitive areas of the mold, such as the material inlet and air outlet. Multimaterial molds that reduce the UV intensities in nonmodel parts have longer lifespans. Also, the shield around a mold's model area is most prone to cracks because it is thin and transparent to UV light.

We observed during our evaluations that a thickness of 2 mm of printed VeroClear is resistant enough for repetitive use. During our experiments, we used the spoon mold (single material) seven times to fabricate different instances of the same object, and the mold was still reusable.

In the future, we plan to test a long list of additive components within our framework. Full automation of the FabSquare process is also a promising direction of future work, with potentially significant commercial impact. Ultimately, we hope that computer graphics scientists find FabSquare a useful tool for their studies. 

Acknowledgments

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