Platener: Low-Fidelity Fabrication of 3D Objects by Substituting 3D Print with Laser-Cut Plates

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ABSTRACT

This paper presents Platener, a system that allows quickly fabricating intermediate design iterations of 3D models, a process also known as low-fidelity fabrication. Platener achieves its speed-up by extracting straight and curved plates from the 3D model and substituting them with laser cut parts of the same size and thickness. Only the regions that are of relevance to the current design iteration are executed as full-detail 3D prints. Platener connects the parts it has created by automatically inserting joints. To help fast assembly it engraves instructions. Platener allows users to customize substitution results by (1) specifying fidelity-speed tradeoffs, (2) choosing whether or not to convert curved surfaces to plates bent using heat, and (3) specifying the conversion of individual plates and joints interactively.

Platener is designed to best preserve the fidelity of *functional* objects, such as casings and mechanical tools, all of which contain a large percentage of straight/rectilinear elements. Compared to other low-fab systems, such as faBrickator and WirePrint, Platener better preserves the stability and functionality of such objects: the resulting assemblies have fewer parts and the parts have the same size and thickness as in the 3D model.

To validate our system, we converted 2,250 3D models downloaded from a 3D model site (*Thingiverse*). Platener achieves a speed-up of 10x or more for 39.9% of all objects.

Author Keywords: rapid prototyping; 3D printing; building blocks; physical prototyping.

ACM Classification Keywords: H5.2 [Information interfaces and presentation]: User Interfaces.

INTRODUCTION

Personal fabrication tools, such as laser cutters and 3D printers [5], allow users to prototype one-off objects and to iterate over designs. While there is a range of fabrication machines, 3D printers are the most versatile in that they allow creating arbitrary 3D shapes. Because of this benefit,
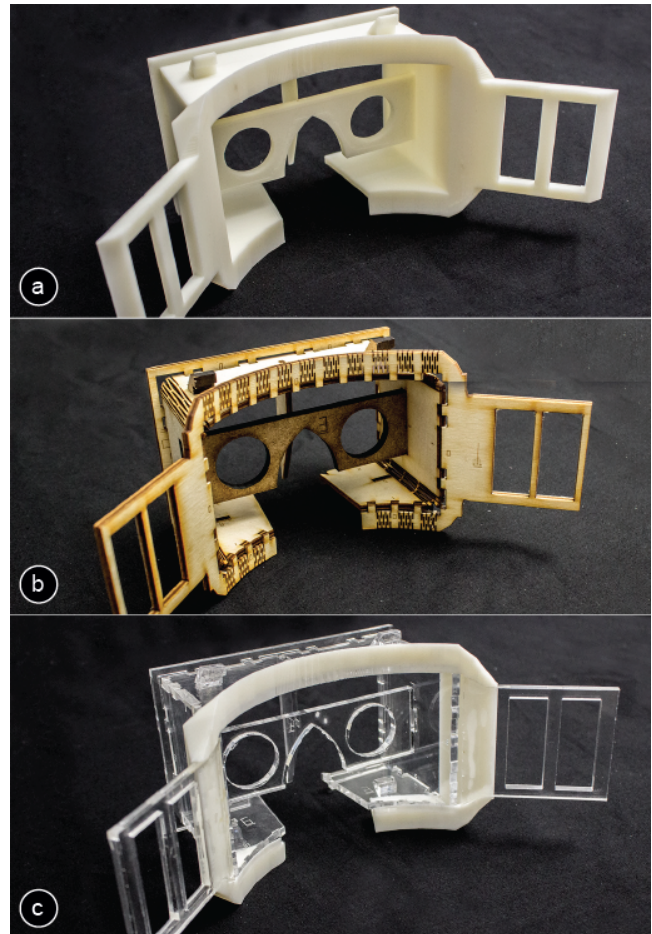
Figure 1: Platener speeds up the fabrication process by substituting parts of 3D models with straight and curved plates that can be fabricated quickly on a laser cutter. Here Platener optimizes (a) the 3D model of a head mounted display body for (b) quickly testing the ergonomic fit of the forehead piece, and (c) for evaluating the industrial design of the forehead piece.

thousands of 3D models for 3D printing are available on sharing sites, such as *Thingiverse*.

While for some types of objects, such as 3D scans of people, the full expressiveness of a 3D printer is crucial, this is less the case for types of objects that are defined by their technical function, such as casings and mechanical tools. At the same time, these types of objects often require extensive iteration, as they have to match exact specifications

and constraints. A case, for example, has to fit its contents, and a gearbox has to be sturdy enough to bear a load.

3D printers tend to be too slow for fast design iteration. Many objects print over night, limiting users to a single design iteration per day. Researchers therefore proposed speeding up the early stages of design by fabricating *simplified* representations for intermediate versions. Only the regions that are of interest in the current design iteration are fabricated in full detail. This concept is referred to as *low-fidelity fabrication* or *low-fab* [15]. FaBrickator, for example, substitutes 3D print material with Lego bricks [17], while WirePrint prints 3D models as wireframes [15].

Unfortunately, faBrickator and WirePrint produce only very coarse approximations as both of them convert 3D models into a coarse grid of Lego bricks or wireframe meshes. For functional objects this is often not sufficient. Approaches from computer graphics that preserve surface contours, e.g., by folding paper strips [14] represent the shape of an object better, but since they are generally hollow inside do not preserve the technical function of an object either.

In this paper, we present a low-fab method designed specifically for functional objects. By replacing parts of the 3D model with laser-cut plates of the same dimensions and thickness and by keeping the number of parts low, Platener preserves many of the aspects relevant to functional objects.

PLATENER

Platener speeds up fabrication by converting a model designed for 3D printing entirely or in part to a 2D representation that can be fabricated using a laser cutter. Figure 1b illustrates this at the example of a head-mounted display body. Platener created this version by extracting straight and curved plates from the 3D model and substituting them with laser cut parts of the same size and thickness. This approximates the stability of a 3D print of the same model well and largely preserves its function (see Figure 2).

Figure 2: The head-mounted display created using Platener, ready to be worn.

However, the Platener model can be produced using a laser cutter, allowing for much faster fabrication. Platener allows producing this head-worn display in 20 min (15 min cutting plus 5min manual assembly), which is 44 times faster than the 3D print (14:30h) the model was designed for.

Platener returns the 3D model in the form of one or more 3D printable .stl files and laser cuttable .svg files, which can be sent directly to the 3D printer and laser cutter. Figure 3 illustrates this at the example of the head-mounted display body from Figure 1c.
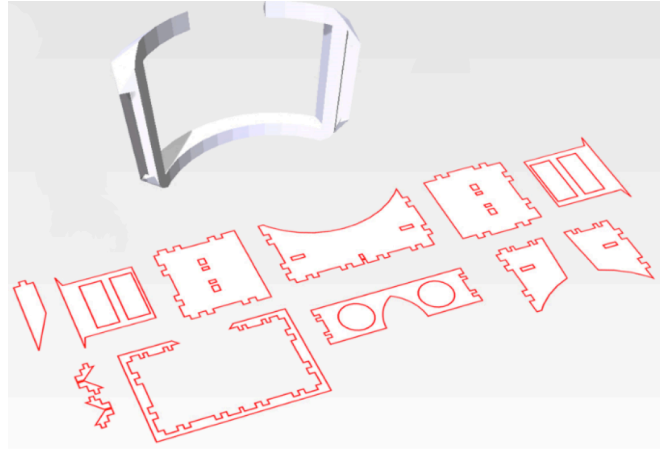

Figure 3: Platener exports 3D printable parts and laser-cut parts as .stl and .svg files, here the model from Figure 1c.

Adapting the conversion to the current design phase

To best suit the needs of the current design phase, Platener allows users to convert 3D models under different settings. For an early design phase, for example, users may convert their models with speed in mind; in later phases they may gradually shift the emphasis to fidelity. Note that here fidelity refers not only to shape but also to other physical property such as appearance, structure, and material.

As an example, Figure 1 shows three different versions of the head-mounted display. They were generated from the same 3D model, but with different fidelity-speed settings. Platener allows users to specify these trade-off settings using a global slider.

Speed-fidelity: Setting this slider all the way to "fidelity" (Figure 4a) produces an object that is all 3D printed, which trivially preserves fidelity, but obviously at the expense of having no speed-up. Moving the slider towards "speed" causes Platener to initially replace very large regions with individual laser-cut plates (Figure 4b); then more and more regions get replaced, resulting in increasingly higher speed-ups (Figure 4c). Platener performs this in interactive speed, i.e., as the user is dragging the slider, Platener continuously updates the model. This allows users to see the changes right away and thus to quickly find the conversion that best suits their needs.
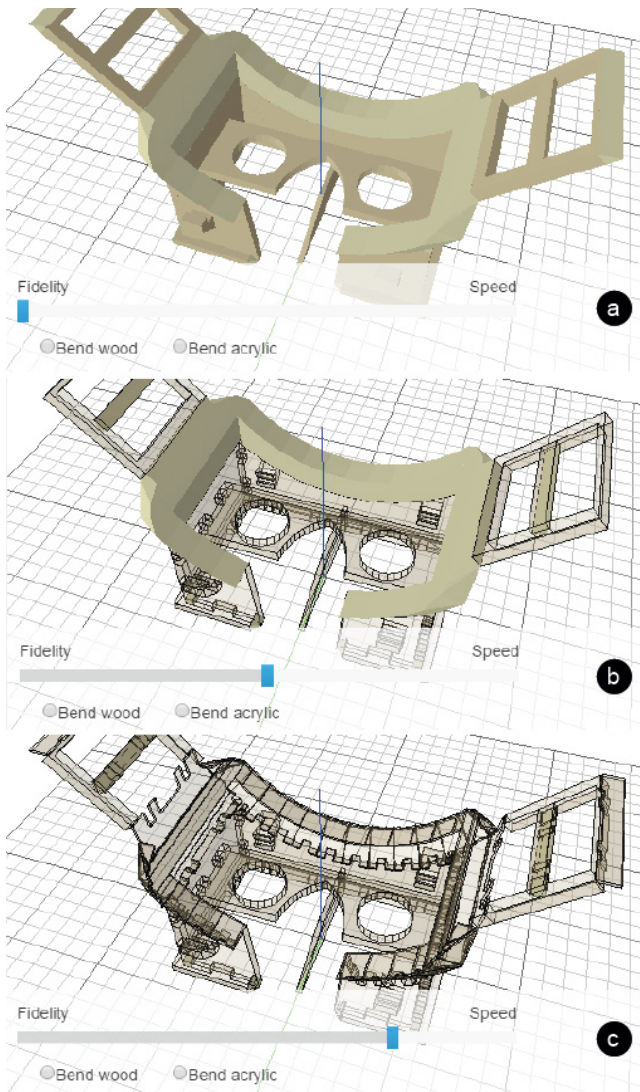
Figure 4: Platener's user interface provides users with a global slider to define the fidelity-speed trade-off.

Curved surfaces: Platener also provides options for handling curved plates. When the curved plate option is deactivated, Platener approximates curved plates using individual plates connected by finger joints (Figure 4c). Activating the curved plate option causes Platener to convert cylindrically curved regions in the 3D model to one plate that can be laser-cut and bent.

Curved plates come in two styles: The first option *bend acrylic* fabricates a flattened version of the respective surface using the laser cutter that can then be bent using a heat gun. As illustrated by Figure 5, users (a) cut the pieces, (b) heat them up using a heat gun or strip heater [3], (c) pre-shape them along the dashed instruction lines Platener provided, and (d) press them into the corresponding positions in the model, which gives them the desired shape.
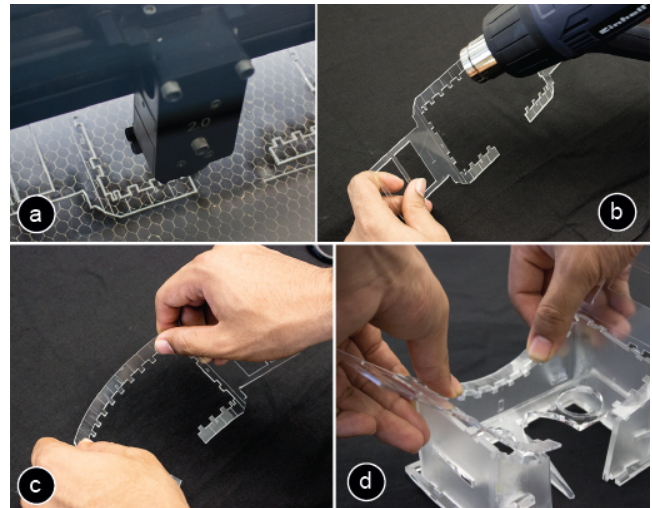

Figure 5: Creating a curved plate from acrylic: (a) cut plate, (b) heat it using a heat gun, (c) pre-curve it, and (d) press it into position to give it the right shape.

The second curved plate option uses a wooden living hinge. As illustrated by Figure 6, for this to work, Platener cuts a dense pattern of living hinges into the plate. This results in a plate that is flexible along the intended dimension [10]. In this case, users only have to (a) cut the curved plate and then (b) mount it using the provided finger joints.
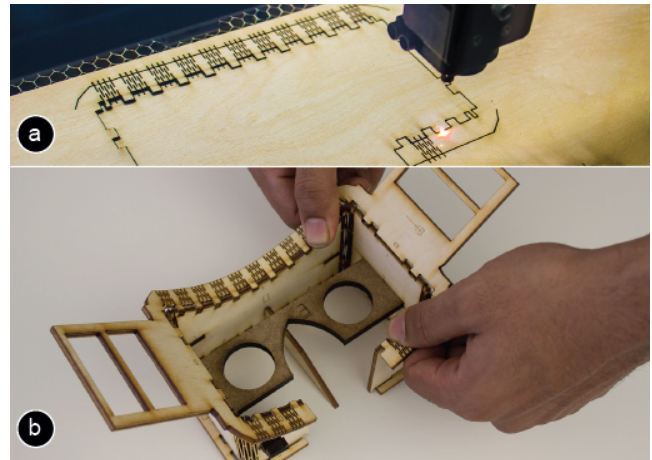

Figure 6: Creating a curved plate from wood. (a) Cut the object on the laser cutter, (b) mount it into position.

As shown in Figure 7, Platener helps users assemble parts by embedding matching pairs of labels.

Figure 7: Platener 3D prints/engraves instructions.

Specifying the *focus* of the current design iteration

On top of these global settings, different design iterations tend to put the focus on different parts [17]. Platener allows users to define such a focus by assigning a specific fabrication technique using *brushes*. For the head mounted display, the global threshold defines that the forehead piece should be 3D printed. Within this context, the user can now choose the focus of the current design iteration:

Case 1: The current design iteration is about some other part, such as the optical path. The forehead piece thus does not matter. In this case, the user can use the *do not print* brush on the forehead piece and the device will be fabricated without this part (Figure 8).
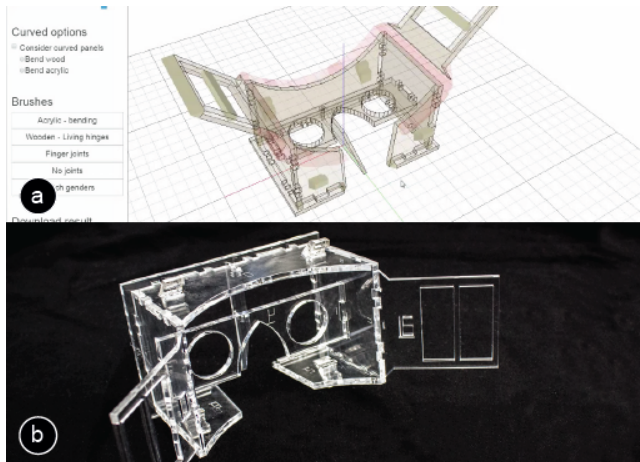

Figure 8: The design iteration does not require the head piece. The user thus uses the *do not print* brush.

Case 2: The current design iteration is about the ergonomics of the forehead piece, thus the contact area of the forehead piece matters. The user has a heat gun and decides to use the *curve acrylic* brush on the forehead piece (Figure 9).
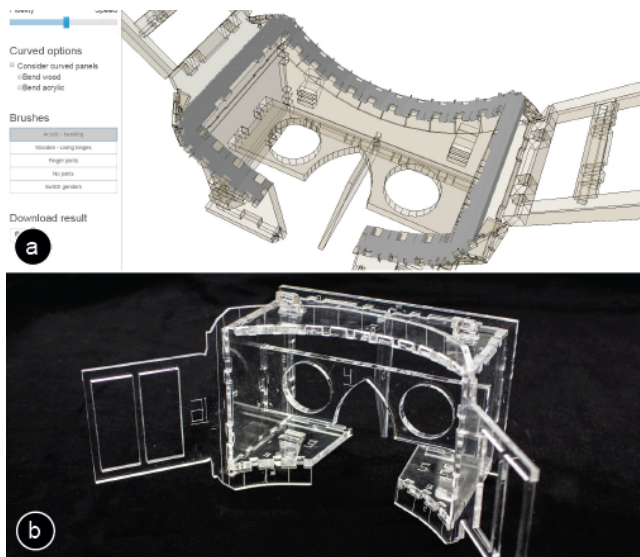

Figure 9: Overwriting the default with the *curve acrylic* brush to obtain a curved version for ergonomic testing.

Case 3: In this round of design, not just the ergonomics, but also the entire industrial design of the forehead piece is in focus. The user thus overwrites the setting of the forehead piece in the last iteration by using the *3D print* brush, resulting in the hybrid object shown in Figure 1c.

Case 4: In yet another round of design, the mechanics and the stability of the object are in focus. Per default, Platener has chosen to represent the four vertical edges of the casing as finger joints. These are easy to assemble, but brittle and thus not a good approximation for the stability of a 3D print. The user handles this by customizing these edges/ connectors, similar to how one customized plates. As shown in Figure 10a, the user uses the *bend acrylic* brush and brushes across the connectors. This causes Platener to merge the four wall segments into a single long strip (Figure 10b). The assembled result is shown in Figure 10c—a version of the head mounted display that is sturdier than any of the converted versions we showed earlier, as its main body consists of only three pieces.
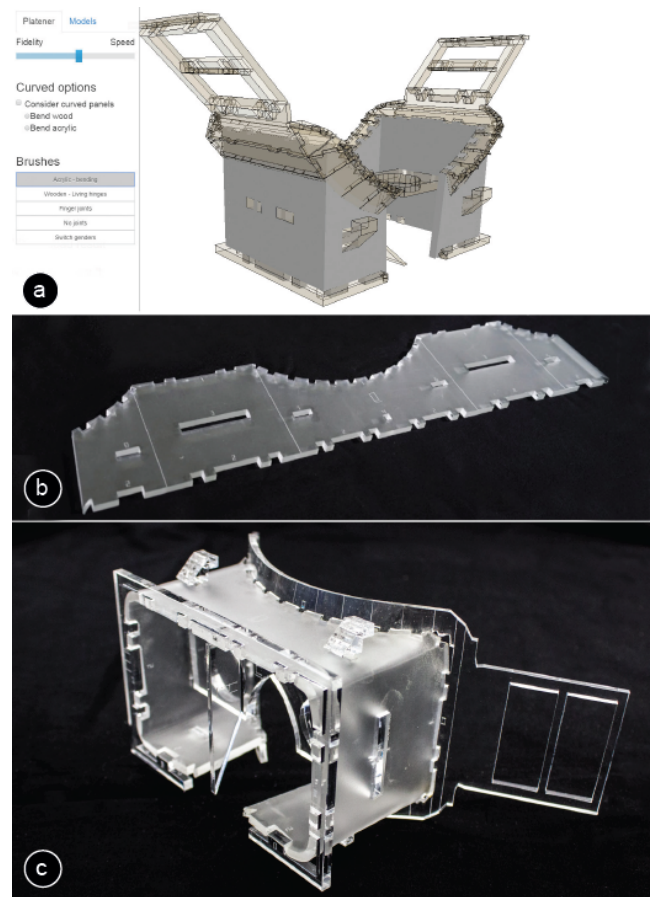

Figure 10: Using the *bend acrylic* brush, the user defines the casing as being made from one piece, which makes it sturdier.

BENEFITS AND CONTRIBUTION

Compared to low-fab techniques from the related work [15,17], Platener generally better preserves a model's geometry. We illustrate this at the example of the three ob-

jects used in the faBrickator paper [17], i.e., the penny ballista (Figure 11), the soap dispenser (Figure 12), and the head mounted display (Figure 13). Platener objects are generally sturdier as they are made from fewer pieces than when using building blocks (penny ballista: 17 plates vs 99 Lego, soap dispenser: 21 plates vs 53 Lego, head mounted display: 9 plates vs 160 Lego). The curved surface, despite requiring more manual effort, results in particularly sturdy results.
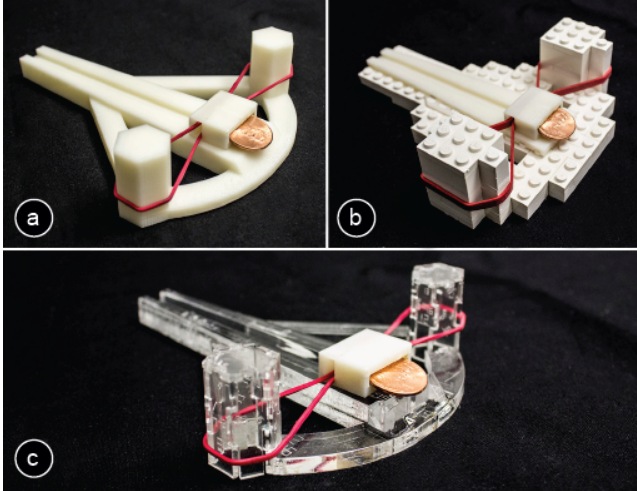

Figure 11: Penny ballista: (a) original 3D model, (b) faBrickator, (c) Platener.

Platener is intended to be a low-fab technique, i.e., users are supposed to use it for intermediate test prints while still iterating, and to only 3D print *the final* version. That said, some objects produced by Platener are of sufficient fidelity that users may choose to use the Platener conversion to fabricate also the final output.
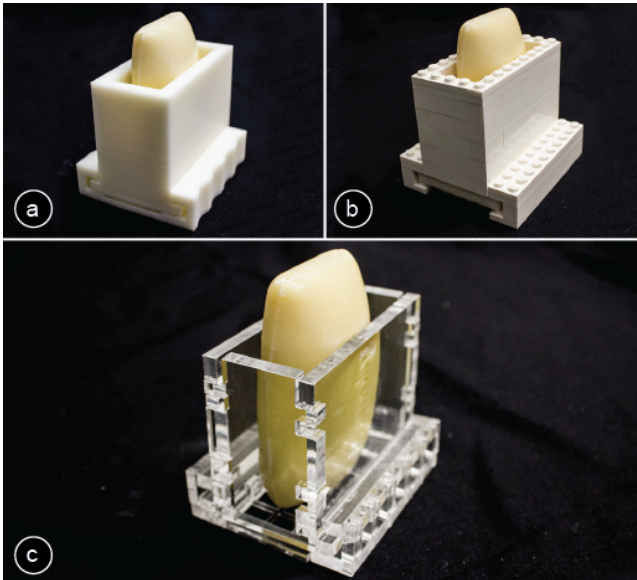

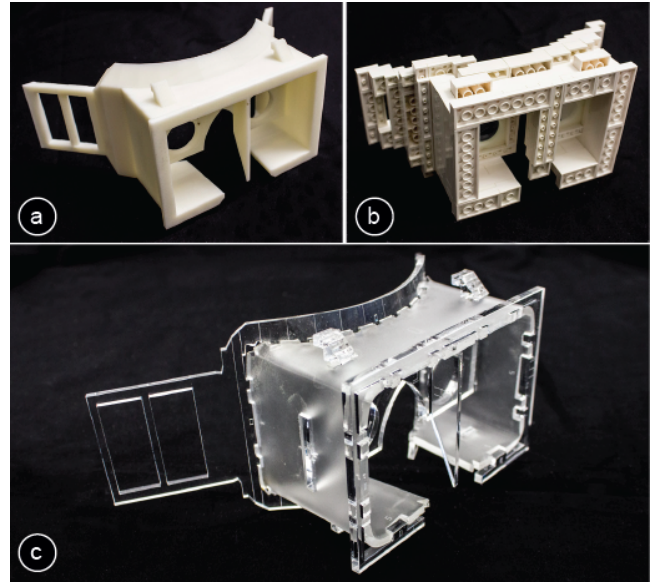**Figure 12: Soap dispenser: (a) original 3D model, (b) faBrickator, (c) Platener.**

Figure 13: Head mounted display: (a) original 3D model, (b) faBrickator, (c) Platener.

On the flipside, Platener is subject to the following limitations: The thickness of the extracted plates is limited to the capabilities of the laser cutter (e.g., 10 mm maximum plate thickness on our ULS PLS6.150D laser cutter). While Platener speeds up design iteration of functional objects, it is less suitable for objects that are solely defined by their shape, such as 3D scans of people.

RELATED WORK
The work presented in this paper builds on personal fabrication, low-fidelity fabrication, and shape approximation.

Personal Fabrication and Laser Cutting
Laser-cutters are used for a wide variety of objects in personal fabrication as they allow users to quickly fabricate objects that fulfill a technical function: Coros et al. [2] show how to fabricate animated mechanical toys using laser cutters, *SketchChair* [19] shows how to build functional furniture, and *Pteromys* [21] shows how to laser cut functional model airplanes.

Low-fidelity fabrication
Platener shares the same goal as previous low-fidelity fabrication system, which aim at reducing fabrication time by replacing the original 3D representation with an alternative one: faBrickator replaces sub-volumes of a 3D model with Lego bricks [17]. LaserOrigami [16] approximates 3D shape by bending laser-cut 2D using a defocused laser. WirePrint replaces the surface of a 3D model with a wireframe structure [15].

Converting 3D models into stackable 2D plates
The most common approach to represent a 3D model using laser-cuttable parts is to convert it to a stack of 2D plates. This stack is generated by rasterizing/slicing the model along its vertical axis at a fixed interval. This functionality is included in many commercial products, such as the 3D editor *123D Make* [1]. Hildebrand et al. [7] take this ap-

proach one step further by slicing parts of the model in different orientations to better approximate the overall shape. While stackable plates ensure that the volume of a 3D object is well approximated, they are a less accurate surface representation.

Converting 3D models into intersecting 2D pieces

A different representation of a 3D model can be achieved using intersecting planar pieces. The resulting objects require less material and consist of fewer parts and thus are easier to assemble. *SketchChair* [19], for instance, provides a user interface for creating chairs based on intersecting pieces. McCrae et al. [6] and Schwartzburg et al. [20] provide algorithms that guarantee the constructability of designs based on intersecting pieces. *Slices* [12], finally, minimizes the number of pieces based on a study of human perception of shape. For some classes of objects, such as many types of furniture, a representation based on intersecting pieces equals the original shape (e.g., *Furniture Factory* [18] and Lau et al. [9]). Instead of converting an existing 3D model to intersecting pieces, *FlatFitFab* [13] allows users to create 3D models directly from laser-cuttable parts.

Converting 3D models to foldable 2D sheets

To better represent the shape of a 3D model, several systems have been developed to convert 3D models into planar sheets that can be folded into the desired 3D shape. Mitani et al. [14] propose an algorithm that unfolds a 3D model into a set of strips that can be cut out of paper. Besides using hard creases to fold material into 3D shapes, *Curved Folding* [8] proposes to integrate smooth curves in the bending pattern. *Soft folding* [22] combines both approaches and allows users to include creases and soft folds into a flat sheet. While foldable sheets result in an accurate surface representation, they have no infill and are thus not sturdy enough to perform mechanical functions.

Combining different fabrication techniques

In the context of architecture, Martens et al. [11] manually segment a 3D model into both laser-cut and 3D printing parts to make use of the benefits of both tools. Platener facilitates combining different fabrication techniques by automating the substitution.

IMPLEMENTATION

This section describes Platener's core data structure and the implementation of the processing pipeline.

#1 Mesh Segmentation

The mesh segmentation algorithm takes a 3D printable manifold mesh as input and outputs laser-cuttable plates and 3D printable parts. Platener then generates the *plate graph* of the 3D model according to the adjacency relationship of these segments.

The segmentation algorithm first extracts all flat planes from the 3D mesh then identifies *plates* by iteratively grouping plane pairs that are parallel, have an opposite normal, and are within distance d. The variable d represents the thickness of the *plate* and users manually configure it

according to the laser cutting material. Each *plate* consists of two planes. The size and shape of the plate are determined by projecting both planes into 2D and intersecting them. We repeat the algorithm with all planes that remain after intersection until no more planes can be converted to *plates*. After extracting all *plates*, the algorithm labels the remaining parts of the 3D mesh as to *3D print*.

#2 Plate Graph Generation

After the mesh segmentation, Platener constructs a *plate graph* that records the fabrication method for each segment and joints between them. As illustrated by Figure 14, each node in the plate graph represents one part of the 3D model and each edge represents a connector between two plates. Each node has one of the three states: *3D print*, *laser-cut,* or *ignore*. Each edge, i.e., connector, has one of the five states: *no connector, bending connector, finger joint, interlocking joint, bending connector,* or *glue connector*.
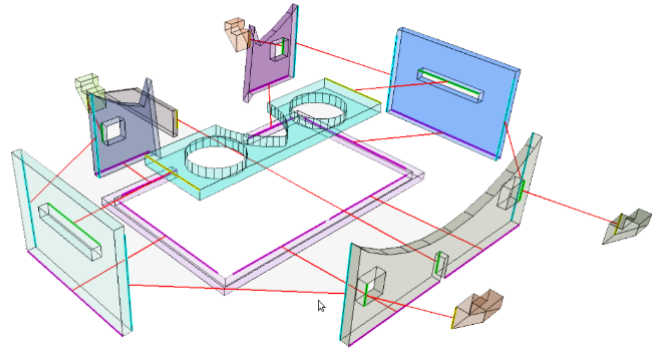

Figure 14: The plate graph represents the 3D model as a graph of nodes (plates) with edges (connectors).

Initially, Platener labels all nodes as *3D print* and all edges as *no connector*. As users move the fidelity-speed slider towards *speed*, Platener gradually labels the largest laser-cuttable segments as *laser-cut* and their adjacent edges as *finger joints*. Similarly, as users manually specify a fabrication method for each part, Platener interactively updates the corresponding labels in the graph.

#3 Mesh Processing

At the end of the process pipeline, Platener processes the mesh segments according to the *plate graph*.

Unfolding Curved Parts

When the curved plate option is activated, Platener gradually unfolds the curved segment onto a 2D plane. Platener also adds the bending lines or the living hinge pattern perpendicular to the unfolding direction. If the 3D segment cannot be unfolded without overlapping itself [4], Platener converts it to 3D printing as a fall back method.

Joint Generation

According to the labels on the edges, Platener places joints between segments or merges segments into a single piece. When the edge is labeled as *no connector*, e.g., both nodes are 3D printed, or *bending connector*, e.g., users applied the *bend acrylic* brush on the joints, Platener merges them into

one single 3D mesh or *plate*. When using *finger joints*, Platener extends the boundaries of the segments and generates finger joints on the overlapping volume. The *interlocking joint* label is used when there is a cross-section between two segments. In such cases, Platener creates a slit on the laser-cut piece, allowing another plate to slide into and interlock with. Finally, in case the overlapping volume is too small, Platener switches to the *glue connector*, i.e., creates flat surfaces on both segments that afford gluing.

TECHNICAL EVALUATION

We evaluated the effectiveness of Platener by analyzing the speed-up after conversion for a range of different models. Given that Platener was designed for functional objects, such as casing and mechanical tools, we focused on 3D models that their creators described in such terms.

3D Meshes from Thingiverse

In order to obtain an objective sample, we downloaded 3D models from the online 3D model repository *Thingiverse*. At the day of the download, *Thingiverse* contained more than a hundred thousand 3D models in total.

We collected the 3D models by searching the website using the site's built-in search box and downloaded the top 200 results. In order to obtain an objective sample, we did not perform any further selection or removal of mislabeled objects at this stage, so our sample represents the "noise" level currently contained in these sites. Also note that many 3D models on *Thingiverse* consist of multiple 3D meshes. We processed them separately without merging them into one single 3D model.

The 10 search terms we used were *box*, *camera*, *controller*, *gadget*, *gear*, *household*, *mechanical*, *phone*, *speaker*, *tool*. We obtained an overall number of 2,250 3D meshes.

Measurements

We evaluated the effectiveness of Platener based on two measurements: (1) *Fabrication Time* before and after conversion, and (2) *Number of pieces* as a metric indicating the manual assembly effort required.

Results

Platener processed all 3D models and generated 3D printable stl files and laser-cuttable svg files. We estimated the 3D printing time with the *slic3r* (http://slic3r.org) g-code simulator, the laser-cut time by the length of the path contained in the svg files, and we approximated the assembly time via the simple formula of number of pieces multiplied by 15 seconds.

Figure 15 shows the time savings achieved by Platener. It shows that 39.9% of the downloaded 3D models achieve a speed up of more than 10x, which is faster than any of the systems in the related work. Another 13.4% achieve a speed up of 3-10x. 22.8% of models result in *no* speed up.
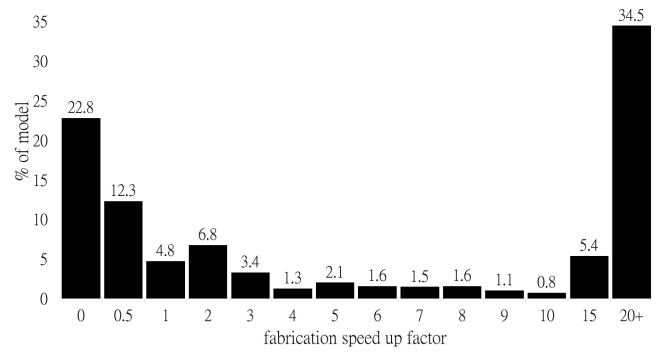

Figure 15: Fabrication time speed up.

Figure 16 shows some example objects that resulted in high speed ups (>10x). These objects consist mainly of flat pieces and contain few parts that cannot be laser cut.
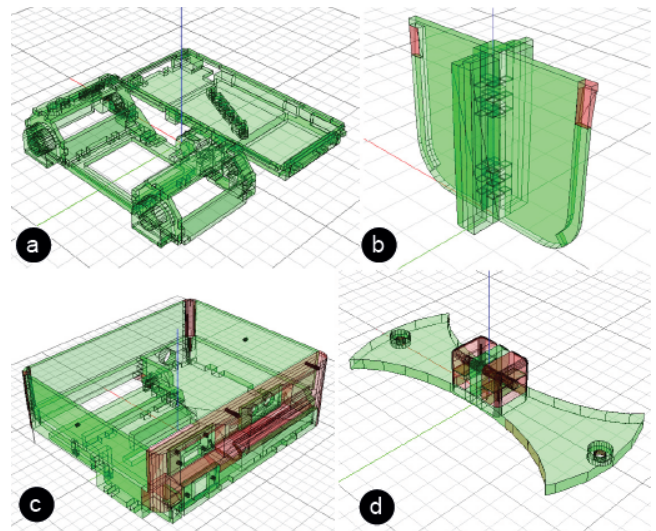

Figure 16: Some of the models that Platener fabricated 10x+ faster: (a) camera body, (b) hardware divider, (c) raspberry pi casing, (d) mount.

In contrast, Figure 17 shows two examples for which Platener was unable to produce any time savings. As expected, these objects are characterized by spherical curvature—shapes that lie outside of what Platener was designed to handle.
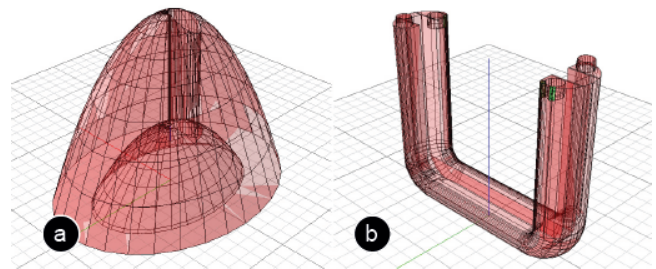

Figure 17: We would not use Platener for these objects as conversion results in no time-savings: (a) cone shaped mini heater part, (b) Kindle Fire comfort grip.

Converted objects consisted on average of 12 pieces, which we approximate with 3 minutes of assembly time.

In summary, our results show that Platener achieves faster fabrication time for many functional objects, making it a useful tool for substantially speeding up the prototyping workflow.

CONCLUSION AND FUTURE WORK

In this paper we presented Platener, a system that allows users to quickly fabricate intermediate design iterations of 3D models by extracting straight and curved plates from the 3D model and substituting them with laser cut parts. We showed that Platener preserves the technical function of an object better than existing low-fab techniques, such as faBrickator: objects converted with Platener have (1) fewer parts and thus are more sturdy, and (2) have a better approximated shape since Platener uses plates that have the same thickness as the extracted volume from the 3D model. Finally, our evaluation shows that for 39.9% of 2,250 objects downloaded from Thingiverse, Platener achieves a speed up of 10x or more, while on average requiring an estimated 3 minutes of assembly time.

For future work, we plan to conduct a formal evaluation that will help us understand how Platener and other low-fab systems influence the design process, i.e., if speeding up fabrication leads to a more trial-and-error oriented design process rather than extended prior thinking. We also plan to integrate materials that only exist for laser cutting but not for 3D printing (e.g., fluorescent acrylic). Integrating LaserOrigami would also make an interesting addition.

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