HingeCore: Laser-Cut Foamcore for Fast Assembly

Muhammad Abdullah, Romeo Sommerfeld, Bjarne Sievers, Leonard Geier, Jonas Noack, Marcus Ding, Christoph Thieme, Laurenz Seidel, Lukas Fritzsche, Erik Langenhan, Oliver Adameck, Moritz Dzingel, Thomas Kern, Martin Taraz, Conrad Lempert, Shohei Katakura, Hany Mohsen Elhassany, Thijs Roumen, and Patrick Baudisch
Hasso Plattner Institute University of Potsdam, Germany
{firstname.lastname}@hpi.de

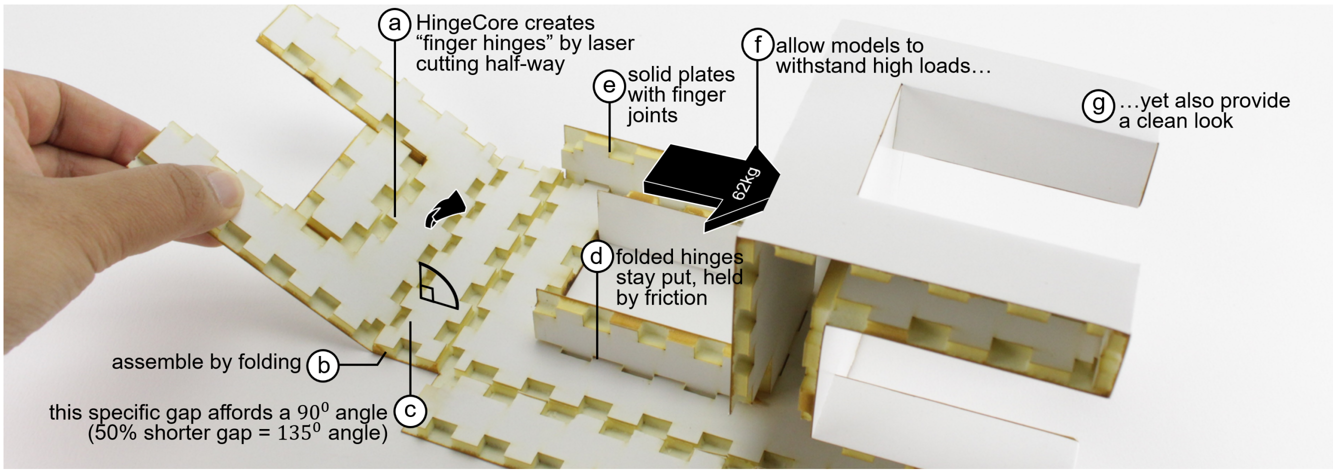

Figure 1: HingeCore is a novel type of laser-cut structure, the key element of which is what we call finger hinges. We produce finger hinges by laser-cutting foamcore “half-way”. Our software HingeCoreMaker automatically converts 3D models into such 2D cutting plans. The resulting models are particularly easy and fast to assemble, while also being sturdy.

ABSTRACT

We present HingeCore, a novel type of laser-cut 3D structure made from sandwich materials, such as foamcore. The key design element behind HingeCore is what we call a finger hinge, which we produce by laser-cutting foamcore “half-way”. The primary benefit of finger hinges is that they allow for very fast assembly, as they allow models to be assembled by folding and because folded hinges stay put at the intended angle, based on the friction between fingers alone, which eliminates the need for glue or tabs. Finger hinges are also highly robust, with some 5mm foamcore models withstanding 62kg. We present HingeCoreMaker, a stand-alone software tool that automatically converts 3D models to HingeCore layouts, as well as an integration into a 3D modeling tool for laser cutting (Kyub [7]). We have used HingeCoreMaker to fabricate design objects, including speakers, lamps, and a life-size bust, as well as structural objects, such as functional furniture. In our user study, participants assembled HingeCore layouts 2.9x faster than layouts generated using the state-of-the-art for plate-based assembly (Roadkill [1]).

UIST '22, October 29–November 02, 2022, Bend, OR, USA

ACM ISBN 978-1-4503-9320-1/22/10…$15.00
https://doi.org/10.1145/3526113.3545618

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); Interactive systems and tools.

KEYWORDS

Personal fabrication, laser cutting, rapid prototyping, manual assembly

ACM Reference Format:
Muhammad Abdullah, Romeo Sommerfeld, Bjarne Sievers, Leonard Geier, Jonas Noack, Marcus Ding, Christoph Thieme, Laurenz Seidel, Lukas Fritzsche, Erik Langenhan, Oliver Adameck, Moritz Dzingel, Thomas Kern, Martin Taraz, Conrad Lempert, Shohei Katakura, Hany Mohsen Elhassany, Thijs Roumen, and Patrick Baudisch. 2022. HingeCore: Laser-Cut Foamcore for Fast Assembly. In *The 35th Annual ACM Symposium on User Interface Software and Technology (UIST '22), October 29–November 02, 2022, Bend, OR, USA.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3526113.3545618

1 INTRODUCTION

The key objective behind rapid prototyping is to enable users to fabricate, test, and iterate rapidly. Rapidity matters, as it allows additional iteration, which increases the quality of the resulting product ([14], [17]). A major goal in research has therefore been

Figure 2: HingeCore objects created using HingeCoreMaker are not only fast to assemble, but also surprisingly sturdy. This allows building structural objects such as (a) toy horses, (f) guitar stands and (h) functional stools. HingeCore also offers a clean look, which allows creating (e) architecture models, as well as design objects, such as (c) lamps and (g) speakers. (b) The white exterior also invites coloring using art markers. The large unicorn and the stool were made from 10mm, all other models from 5mm foamcore.

to make prototyping as fast as ever possible (e.g., WireFab [27], StackMold [57]).

This desire for rapidity in prototyping has been driving the adoption of laser cutting, a technology that is inherently fast, because it produces entire plates at once (e.g., Platener [8], LaserFactory [34]). In recent years, laser cutting received further speed-ups from specialized modelling software that allows users to create 3D laser-cut models efficiently in 3D and then generate the required 2D cutting plans automatically (e.g., FlatFitFab [29] and Kyub [7]).

With fast design and fast fabrication in place, assembly of laser-cut models has now become the new bottleneck that stands in the way of even faster prototyping. The dollhouse 23-part chair model described in Roadkill [1], for example, took study participants 9:54min to assemble, even though plates were already laid out for optimal assembly [1]: this is longer than modeling (<3min in Kyub [7]) and laser cutting of this model combined (<3min on a 120W Trotec Speedy 360 [55]).

In this paper, we tackle this bottleneck, i.e., we further speed up assembly. Drawing inspiration from the folding of thick materials (also known as rigid origami [53] [21]), as well as from multi-depth cutting (Foldem [41]), we present HingeCore. As illustrated by Figure 1, HingeCore is a novel type of laser-cut 3D structure. Its key design element is what we call the finger hinge, which we produce by laser-cutting paper-foam-paper composites (aka foamcore) "half-way". In our user study, participants assembled HingeCore layouts 2.9x faster than layouts generated using the state-of-the-art for plate-based assembly (Roadkill [1]).

We also present a stand-alone software tool called HingeCoreMaker that automatically converts 3D models to 2D HingeCore cutting plans, as well as an integration into a 3D modeling software for laser cutting (Kyub [7]). As illustrated by Figure 2, we have used HingeCoreMaker to create a range of design objects, such as audio speakers and lamps to a life-size bust, as well as structural objects, such as functional furniture and a rideable toy horse.

2 HINGECORE

Figure 1 illustrates the key design element of HingeCore, the finger hinge, which we produce by (a) laser-cutting foamcore "half-way". When folded, the fingers on one side slide between the fingers on the opposite side, where they stay put, based on friction.

1. This basic principle allows for very fast assembly, because (b) finger hinges allow models to be assembled by folding across a pre-scored edge, (c) finger hinges stop folding at a predefined angle, allowing the resulting model to take shape, even before all plates are in place, and (d) folded hinges eliminate the need for tabs, as they stay put without glue.

2. As the same time, (e) resulting models are very sturdy, as they are constructed from solid plates and because of the finger structure in finger hinges, (f) allowing the result to withstand high loads.

3. Finally, (g) finger hinges produce a clean look as there are no exposed finger joints. As illustrated by Figure 2, this clean look makes HingeCore suitable for (e) architectural models and other design objects, such as (c) lamps and (g) speakers, while also (b) allowing models to be painted with common markers, a favorite for kids.

Figure 2 also illustrates HingeCore being used to create sturdy objects, despite being assembled from comparably light and weak foam material. The resulting objects, such as (h) stools, (f) guitar stands, or (a) toy horses are all functional and support human weight. This robustness is the result of the embedded, hidden finger joints, making HingeCore sturdier than any other types of rigid origami.

In addition to finger hinges, HingeCore offers three additional design elements, i.e., slanted geometry, round edges, and cut-outs (see Section "Additional design elements"), allowing HingeCore to support producing a wide range of 3D models designed for generic plate-based laser cutting.

We begin with taking a closer look at finger hinges.

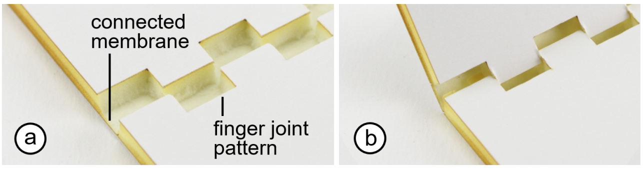

Figure 3: (a) Finger hinges. (b) The connected membrane pre-aligns the fingers. During assembly they slide into each other.

2.1 Finger hinges allow for fast assembly

Figure 3a shows a close-up of a finger hinge. It consists of a finger joint pattern with a thin foldable membrane, that connects the plates. (b) Users assemble finger hinges by holding the material in roughly the right orientation and applying a bending force. This causes the material to crease along the edge hinted by the incision, and the fingers to engage with each other.

The foam layer is reasonably compliant, allowing the fingers to slide into each other with moderate resistance. As illustrated by Figure 4, this eliminates time-consuming gluing or insertion of tabs, which speeds up assembly even further. The compliance of foamcore also makes finger hinges easy to assemble, irrespective of potential variations in kerf [44].

Figure 4: Traditional tabs (a) require gluing or (b) skillful insertion into the opposite tab. (c) Finger hinges, in contrast, stay put based on friction, eliminating the need for tabs.

2.2 Finger hinges are particularly sturdy

In addition to being fast to assemble, HingeCore layouts are also sturdy. As illustrated by Figure 5, the main strength of HingeCore is that the paper layer, which extends across hinges, greatly increases the tensile strength.

Figure 5: HingeCore models resist tension: (a) While traditional finger joints are weak against tension, (b) Finger hinges, connected with paper layers on two sides or (c) four sides enhance the object's resistance against tension by factors of 23.4x and 82x, respectively. (The force sensor shown is a forceX 2.30.)

We validated these claims by fracture testing a cube, which produced the following results: (a) Traditional press-fit finger joint designs without hinges are weak against tension (<0.5kg, depending on the tightness of the press-fit [2]). (b) The paper layer, in contrast, offers high tensile strength [42]. For geometries featuring two opposing connected hinges, this enables joints to withstand a surprising 114N = 11.7kg of tension (c) Geometries featuring four connected hinges even withstand 402N = 41kg of tension.

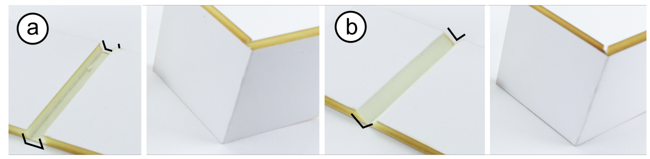

Figure 6: Alternative hinge designs we explored include (a) butt joint hinges, which are simpler to create and (b) miter joint hinges, which provide a precisely folded edge.

With HingeCore's strength stemming primarily from the paper layer, HingeCore does not have to rely on the fingers being properly jammed. This again makes HingeCore less sensitive to variations in kerf than more traditional laser-cut materials, such as plywood or acrylic.

HingeCore models are also very sturdy against compression and shearing, because of the specific design of the finger hinges. Figure 6 illustrates this by showing the two alternative hinge designs we have explored in comparison to finger hinges. All three designs have their own particular benefits: (a) Butt joint hinges are particularly simple to create, as they only require removing a single cuboid-shaped piece of material, while (b) Miter joint hinges result in the cleanest edge when assembled.

The reason we opted for finger hinges is that they result in the sturdiest designs. Figure 7 illustrates this: (a) when miter joint hinges or (b) butt joint hinges are exposed to shearing forces, the glued edges slide with respect to each other and the material breaks. (c) Finger hinges, in contrast, consist of fingers that prevent the material from shearing. This allows them to withstand 1.8x times higher compression loads than butt joint hinges and even 3.6x times higher compression loads than miter joint hinges. (d) This allows the chair from Figure 1 to withstands 62 kg of compression load.

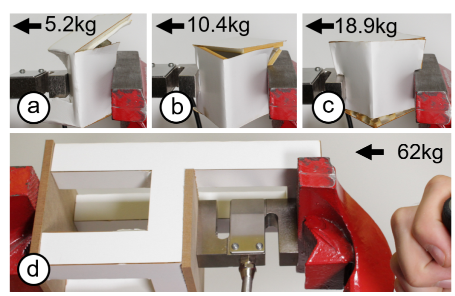

Figure 7: Compression and shearing loads: (a) Miter joint hinges and (b) butt joint hinges are weak against shearing forces and withstand only 5.2kg and 10.4kg, respectively. (c) Finger hinges are strong against shearing and withstand higher compression loads. (d) This allows the chair model from Figure 1 to withstand 62kg of compression. (All boxes measure 6x6x6cm and are made from 5mm Foamcore).

Finally, miter and butt joint hinges need to be glued to stay in place [33], while finger hinges stay put based on the friction between fingers, allowing for faster assembly.

As illustrated by Figure 8, finger hinges pay for their additional sturdiness with a slightly "wiggly" edge. HingeCore resolves this issue in part by "hinting" the material, i.e., it adds another thin laser line in the center of the hinge (aka "scoring") to hint to the material where to crease.

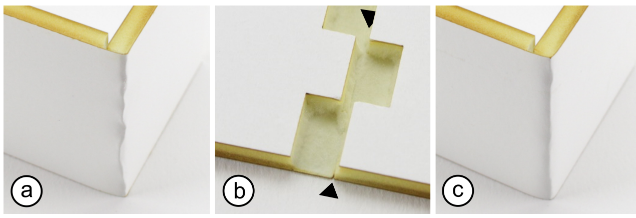

Figure 8: (a) The outer paper layer of finger hinges accommodates the fingers leading to a slightly crooked look. (b) Scoring along the inside of the edge (c) reduces this.

2.3 The mechanics of cutting HingeCore layouts

As shown in Figure 9, HingeCoreMaker uses three types of cut lines to create layouts. (a) Red lines are the same as in traditional laser cutting—they instruct the laser to cut through all the layers. (b) Magenta lines cut "half-way", i.e., they are precisely calibrated to cut through the top paper layer and the foam layer, while leaving the bottom paper layer intact. The magenta line is instrumental in creating finger joints. (c) Blue lines, finally, score the middle of the hinge (see above), creating a crease to help with folding precise edges.

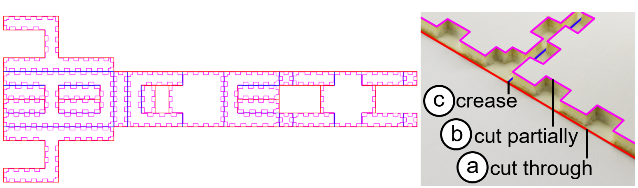

Figure 9: HingeCore Cutting plans use (a) red lines to cut through all layers, (b) magenta lines to cut through the top two layers, and (c) blue lines to score.

While the laser cutter settings for cutting through (red) and scoring the crease (blue) are somewhat flexible, performing half-way cuts (magenta) requires a precise power/speed combination (we used 60% power and 5% speed on our Trotec Speedy 360, 120W). We furthermore recommend fixating the foamcore sheets in the laser cutter by placing weights on the material to ensure it is flat. Finally, we sort the paths inside the SVG export such that the laser cutter performs the half-way cuts before the cut-through line, as this achieves optimal focus on the half-way cuts, which could otherwise be affected by plates lifting up once cut.

2.4 Removal of residue

As illustrated by Figure 10a, before users can assemble a HingeCore model, the residual material created by finger hinges has to be removed. (b) We initially experimented with polyurethane based Foamcore and burned the residue away using the laser cutter by engraving deeply. (c) In the interest of cutting/engraving time, we then switched to cutting only outlines, and then removed the residue manually using a rotary excavator tool, which we had developed for this purpose. The tool rips out fingers with the help of tiny hooks when rolled across the inside of a finger hinge.

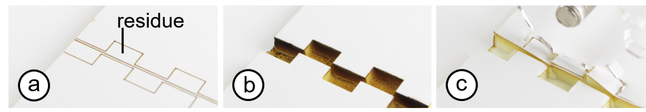

Figure 10: (a) In earlier experiments, we used polyurethane foamcore, which is subject to residue. (b) residue can be burnt off by laser engraving, or (c) removed (by hand or) using this custom rotary tool we created. (We use this type of foamcore throughout this paper, as it offers good visual clarity).

We ultimately switched to the process illustrated by Figure 11. This design uses heat-sensitive (polystyrene-based) foamcore which it shrinks away using a pair of additional half-way cut lines (magenta lines, Figure 9). This shrinks both the foam in the residue and in the adjacent plates, allowing the residue to slide into the resulting cavity in the adjacent plates. This adds little to the cutting time (2 mins for the chair model from Figure 1, for example, on Trotec speedy 360 [55]) and thus allows for fast cutting and fast assembly.

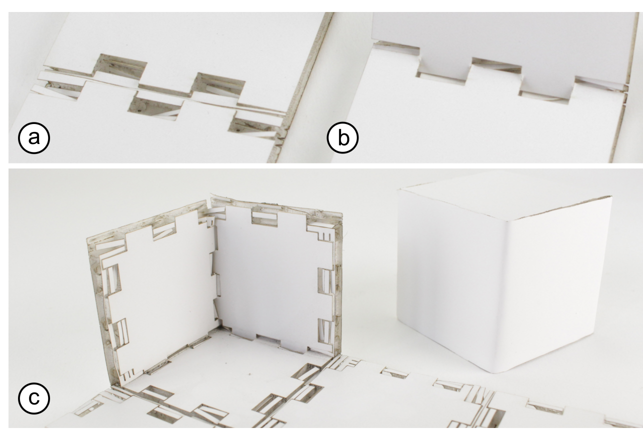

Figure 11: (a) Foamcore made from polystyrene shrinks when heated. Two additional half-way cut lines across the fingers shrink all residue in place. (b) this allows folding to crush finger hinges between the opposing fingers. (c) An example model created using this technique.

3 ADDITIONAL DESIGN ELEMENTS

While we have so far focused exclusively on (convex) finger hinges, we have developed four additional design elements, to allow for a broader range of 3D models to be fabricated as HingeCore, such as those shown in Figure 2.

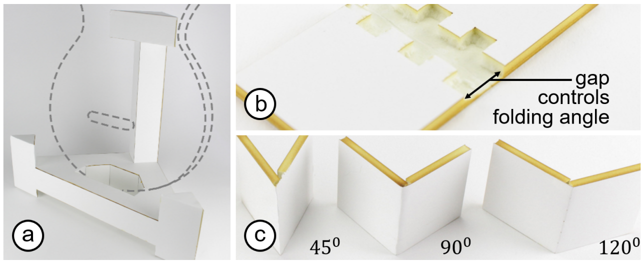

Figure 12: (a) HingeCore also allows for slanted geometry. (b) Adjusting the gap between the fingers of HingeCore's finger hinges (c) predetermines the folding angle.

3.1 Slanted geometry

While the chair example from Figure 1 only contained 90-degree angles, HingeCore supports slanted geometry as well. As shown in Figure 12, HingeCore inserts a gap of appropriate length between finger joints. During assembly, these gaps cause the fingers to stop the user's folding actions at the intended bending angle. This makes it easy and fast to form the intended angle and thus further speeds up assembly.

3.2 Downwards hinges are straight

Models containing concave features, require hinges that are folded downwards. As shown in Figure 13, HingeCore achieves this using a straight-cut hinge. This design cannot be folded up, thereby affording folding down. This eliminates the necessity to use visual markings, as used by traditional folding styles (e.g., mountain and valley lines [22]).

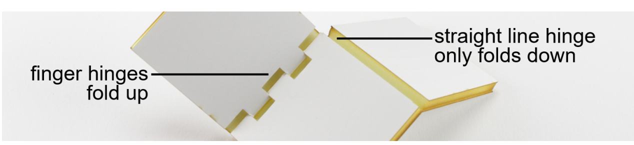

Figure 13: Finger hinges afford folding up, while straight line hinges only allow folding down.

Given the additional qualities of the finger hinges, the HingeCore algorithm (see Section "Algorithm") prefers generating finger hinges over downwards hinges when generating layouts.

3.3 Round geometry and cut-outs

As illustrated by Figure 14, HingeCore also supports the creation of round geometry. (a) HingeCore achieves this by creating a pattern of half-way cut lines (magenta) that perforate the paper and foam layer, thereby allowing the material to bend in the intended direction.

The required distance between cut lines depends on the amount of material removed by the laser, i.e., the kerf. HingeCore uses the following formula to find the appropriate distance between cut lines:

$$\frac{(length\ of\ the\ curve * kerf * 180)}{(material\ thickness * degree\ of\ curvature * \pi)}$$

(b) For curvature generated this way, the remaining strips of paper line up on the inside, which (c) results in a smooth, continuous outside surface that not only features a clean look but is also very sturdy against compression.

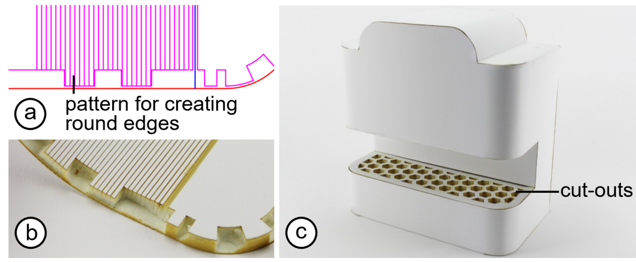

Figure 14: (a) HingeCore creates a pattern with half-way cut lines (magenta), allowing (b) the material to bend. The inner paper layer lines up providing resistance against compression, while (c) the outer paper layer gives a smooth look. HingeCore also allows for cut-outs.

Finally, HingeCore also supports the creation of cut-outs by creating regular (red) cut lines (Figure 14c).

4 USER INTERFACE: HINGECOREMAKER

We have created HingeCoreMaker, a software tool that automatically converts 3D models into 2D HingeCore layouts.

4.1 HingeCoreMaker standalone tool

As shown in Figure 15, HingeCoreMaker works as a web-based headless, drag-and-drop interface allowing users to convert 3D models in common file formats (.obj and .stl). HingeCoreMaker uses CGAL polygon mesh processing [9] to convert input files to its required data structure (half-edge). Like most other laser cutting techniques, HingeCore offers only limited resolution and thus imported models must adhere to this limitation.

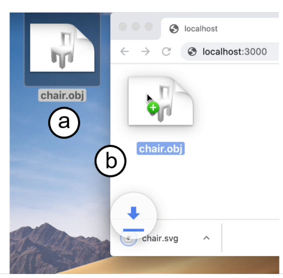

Figure 15: (a) The user drags a file into the HingeCoreMaker web-based tool, which converts the 3D model to a 2D layout and (b) sends the cutting plan.

4.2 Integration into an interactive system

To provide users with additional functionality, such as control over hinge placement, we also created a version with a 3D user interface. We achieved this by integrating HingeCoreMaker into an interactive 3D editor for laser cutting (Kyub [7]).

As shown in Figure 16a, users access HingeCoreMaker's functionality by setting the material of their model to foam-core. (b) The

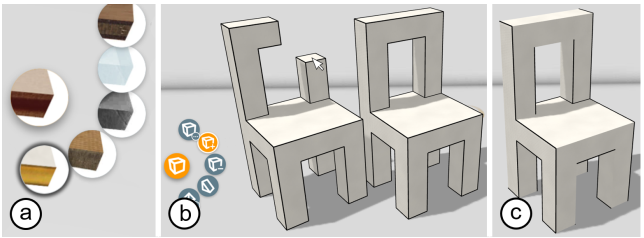

Figure 16: (a) The user selects the "Foamcore" material and then (b) models the chair, here using the Kyub "add boxel" tool [7]. (c) When done, HingeCore automatically places hinges vs. cuts (allowing it to "unfold" the model into the 2D representation shown in Figure 9)

integration allows users to continue to apply Kyub's standard tools to their model, ensuring that the design process remains the same. (c) Once users are done modeling, HingeCoreMaker automatically creates a 2D "unfolding", i.e., where to fold and where to cut. The integration visualizes directly on the 3D model using black lines to indicate seams, while white edges indicate hinges. HingeCoreMaker then exports the model as a 2D layout to the cutter.

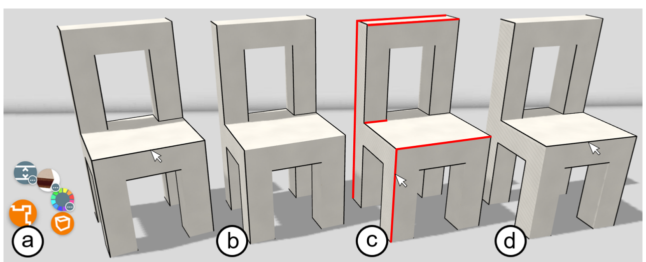

Figure 17: (a) The "connect edge" tool (b) allows users to toggle edges between hinge and seam. (c) If a hinge is not feasible (e.g., forming a loop), our system highlights all conflicting hinges. (d) Users resolve the conflict by toggling another edge.

As illustrated by Figure 17a and b, we added a "connect edge" tool to the system. It allows users to toggle an edge between seam and hinge by clicking it. This allows users to optimize models for appearance and/or sturdiness. (c) If a hinge makes the model non-developable or results in overlap in the 2D unfolding, our system highlights all conflicting edges (in red). (d) Users resolve the conflict by clicking any of the highlighted edges, turning it back into a seam.

As illustrated by Figure 18, HingeCoreMaker is compatible with the full range of Kyub tools, allowing users to create the aforementioned (a) rounded edges, (b) cut-outs, and (c) slanted geometry.

5 CONTRIBUTIONS, BENEFITS, & LIMITATIONS

In this paper, we make the following contributions. (1) We introduce HingeCore and its key design element: the finger hinge. Finger hinges allow for very fast assembly, while also producing sturdy results. We complement finger hinges with additional design elements

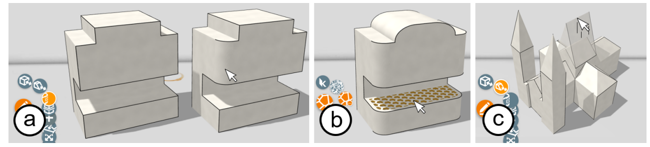

Figure 18: HingeCore supports the creation of (a) rounded edges, (b) cut-outs and (c) slanted geometry.

such as straight cut hinges, regular finger joints, slanted geometry, rounded elements, and cuts-out, allowing us to reproduce a wide range of 3D models designed for (generic plate-based) laser cutting. (2) We present an algorithm for converting 3D models to HingeCore Layouts and implement it in the form of a stand-alone software tool called HingeCoreMaker. We integrated HingeCoreMaker into a software system (Kyub [7]), which allows users to create and modify HingeCore objects interactively. (3) We validated our design by fracture testing (see Section "HingeCore"), (4) in a technical evaluation showing the applicability and speed of our algorithm, and (5) in a user study determining that HingeCore enables 2.9x faster assembly.

These benefits translate into a range of application scenarios. On the one hand, HingeCore's high assembly speed is relevant in the context of time-critical rapid-prototyping, such as in classrooms. On the other hand, the clean white and angular look makes HingeCore relevant to applications in industrial design and architecture.

HingeCore is subject to three main limitations. First, while HingeCore allows placing cutouts and engravings on the inside of models, engraving the outside requires flipping the model in the cutter and running a second pass. Second, while HingeCore-Maker is capable of processing mortise-and-tenon joints and cross joints, they always result in separate plates, as their non-manifold geometry [28] prevents them from being implemented using hinges. Third, hinges lead to larger contiguous parts, imposing additional challenges on nesting.

6 RELATED WORK

This work builds on research on speeding up personal fabrication, fabrication with rigid-foldable materials, and unfolding 3D models.

6.1 Speeding up personal fabrication

Fabrication speed is a key research topic in personal fabrication. One approach is to quickly generate prototypes by reducing the level of fidelity, for example by using wire frames (Wireprint [31], On-the-fly print [40], Protopiper [4]). FaBrickation [32] substitutes parts of a model with ready-made building blocks, while Wei et al. [60] minimize what needs to be printed. Ephemeral Fabrication [50] allows models to be recycled easily for quick iterations.

Replacing slow 3D printing with fast techniques such as wire bending (WireFab [27]) and vacuum forming (ProtoMold [66]) further speeds up prototyping. Platener [8] is a particularly interesting example that partially replaces 3D print with laser-cut structures. JigFab [23] speeds up the assembly process by automatically producing jigs.

Laser cutting is fast, because it produces parts by cutting along the perimeter as opposed to filling their volume [6]. Different systems exploit this, such as LaserFactory [34] which integrates pick and place functionality for electronics and assembly within a laser cutter. StackMold [57]is a technique to quickly create molds to produce 3D models. Packable springs [61] creates thin planar spirals which approximate the shape of 3D models when expanded.

2D cutting plans are the de-facto standard format for laser cutting. To speed up the design process of models for cutting, recent research has targeted a transition towards modeling in 3D. In Joinery [67] users specify the connections between joints in a 2D environment, CutCAD [18] lets users model in 2D while previewing the 3D result. FreshPressModeler [11], FlatFitFab [29] and Kyub [7] are full 3D modeling environments for laser cutting. To further transition from 2D to 3D conversion tools such as assembler[3] [45] and autoAssembler [46] have considerably sped up the modelling process. Similar approaches have sped up design for other domains as well ([58], [35], [43], [62]). Stemasov et al., propose removing the modelling process entirely [49].

Roadkill [1] speeds up assembly of laser-cut models by integrating assembly instructions within the layout on the plates. Deadelus in the dark [10] uses a similar approach to enable visually impaired users to assemble models, while FoolProofJoint [39] adjusts the joints in the model to reduce assembly errors.

6.2 Fabrication with rigid-foldable materials

The most common foldable material used is paper and the most common use case is paper craft [51], [52] and more recently metamaterials [47]. To facilitate folding, actuation based on pulling strings [20], heat application ([56], [5]) and robotically [59] has also been explored. Foldio [37] creates foldable interactive objects with embedded electronics, while FoldMold [48] creates foldable molds, reducing the cost of molded objects.

The concept of folding has also been extended to speed up fabrication. Pop-up Print [36] 3D prints objects in a folded state, which reduces the print volume and need for support material. Folding is also employed to create reconfigurable objects, Foldabilizing furniture [25], modifies pieces of furniture allowing them to be flat folded to save space.

Researchers have explored using composite materials to selectively embed functionality in rigid materials. LamiFold [24] incorporating foldable mechanisms, while FoldTronics [65] and LASEC [16] embeds circuitry into honeycomb structures and stretchable surfaces.

Tachi et al., propose a method to construct origami-based hinged rigid-foldable structures [53]. Ku et al., extend this to create crease patterns for thick materials [21]. Muntoni et al., propose using CNC machines to create foldable layouts with glue-able miter joints [33]. Foldem [41] creates multi material composites with rigid and flexible properties by laser cutting halfway. HingeCore extends the concept of rigid-foldable elements by introducing the finger hinge, which enables fast assembly and sturdy construction.

6.3 Unfolding 3D models

Researchers create non-overlapping 2D unfoldings of 3D models by creating cuts either along an edge (edge unfolding) or along a face (general unfolding) [13].

There are a multitude of algorithms that operate based on domain specific heuristics on triangulated meshes (general unfolding). The key insight is that it is possible to re-triangulate the meshes and then create cuts along those triangles. OptCuts [26] proposes a method to reduce distortion in UV mappings while maintaining the connectivity of the layout. In cases that algorithms are unable to create a single connected layout, the model may be segmented into parts that are unfolded separately. Xi et al., use a learning-based approach to tightly couple the process of unfolding and segmentation resulting in fewer parts [63]. Similarly, Takahashi et al., use a genetic-based algorithm to unfold 3D meshes [54], while Xi et al., simplify the problem through mesh convexification [64]. Mitani et al., propose a strip-based approximation approach to generate unfoldings of paper craft toys [30]. Hao et al. employ genetic algorithms to find a collision free folding of polyhedral unfoldings [19]. Fusion 360 slicer [15] is a commercially available software that uses such general unfolding algorithms. HingeCore does not triangulate the mesh of the model as that would create cuts across the surface of the plates, sacrificing the sturdiness of the model.

HingeCore is tuned to unfold closed box structures (which are orthogonal polyhedra [38]), as these structures allow for sturdy construction. As noted by Zachary et al., edge unfolding orthogonal polyhedra is complicated even if the polyhedron is topologically convex [3]. Our approach is inspired by the work of Damian et al., on general unfolding of orthogonal polyhedral meshes [12]. Unlike general unfolding, where cuts are allowed across the surface of the polygons, HingeCore only cuts along the edges of polygons.

7 THE HINGECORE ALGORITHM

The HingeCoreMaker algorithm converts 3D models into a 2D cutting plan. The algorithm employs heuristics that leverage the benefits of the finger hinges, enable sturdy construction, and provide a simple assembly order while maintaining the connectivity of the layout.

The algorithm proceeds in two steps. First the algorithm creates a 2D edge-unfolding, and then it creates the appropriate cut lines to generate the 2D cutting plan. We explain the algorithm at the example of the chair model from Figure 1.

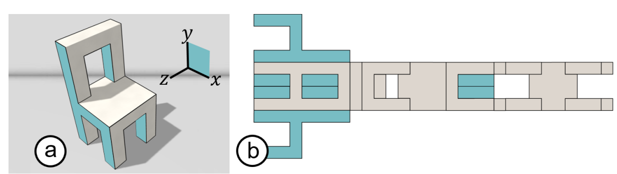

Figure 19: (a) HingeCoreMaker chooses a pair of Cartesian axes (x-y) and designates plates with surface normals parallel to one of them as strip plates (gray). (b) The remaining plates are termed as wing plates (blue).

7.1 Step 1: Create 2D edge-unfolding of the 3D model

As shown in Figure 19a, HingeCoreMaker starts by choosing a pair of "Cartesian axes" (x-y in this case) and uses them to divide the plates in the model into two groups. (b) Plates with surface normals that are parallel to either of the axes are grouped into "strip" plates (gray), forming the main strip of the unfolding. Plates with surface normals orthogonal to the axes are grouped into "wing" plates (blue), which are connected to the strip later. Note that this categorization assumes that all the plates have surface normals that are perfectly aligned with one of the axes of the coordinate system. This is not true for models that have slanted geometry. In this case, HingeCoreMaker picks the axis closest to the surface normal of the plate and uses that for designating it as a strip or a wing plate.

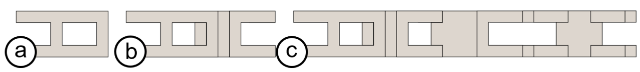

Figure 20: HingeCoreMaker creates the initial unfolding by (a) starting with the plate that has the most connections and (b) iteratively connecting more plates till (c) all plates are part of the unfolding.

HingeCoreMaker forms the initial unfolding from the strip plates: As shown in Figure 20a, HingeCoreMaker starts with the plate that has the highest number of edges connected to other plates in the 3D model, using size as a tie breaker. (b) HingeCoreMaker iteratively adds strip plates to the edges of the current unfolding, discarding plates that cause overlaps with the existing plates in each iteration. Discarded plates are added back to the pool and get connected in a later iteration when other edges become available.

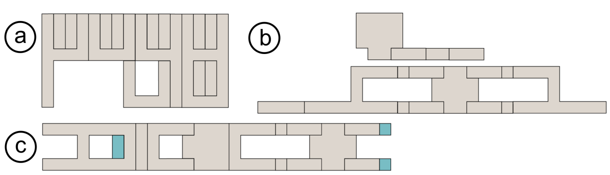

Figure 21: (a-b) HingeCoreMaker creates two additional initial unfoldings using the other two pairs of Cartesian axes (x-z, y-z). (c) HingeCoreMaker chooses the unfolding with the most available edges and fewest sub-unfoldings, removing leaf plates to create more available edge connections in the next step.

(c) HingeCoreMaker repeats the process until no more plates can be added to the strip. Strip plates that remained unconnected in this process are sorted again based on edge connections (and size), and a new plate is chosen to start another unfolding. This process is repeated until all strip plates are part of an unfolding.

As shown in Figure 21a-b, HingeCoreMaker repeats this process for the other two pairs of Cartesian axes resulting in three different unfoldings. HingeCoreMaker chooses the unfolding that has the most available edges (and fewest sub-unfoldings) to proceed to the next step. (c) Finally, strip plates that are connected to one other plate (leaf plates) are removed from the unfolding and added to the pool of wing plates. This step allows HingeCoreMaker to open up as many edge connections as possible for the next step, without breaking apart the initial unfolding.

HingeCoreMaker inserts wing plate candidates: HingeCoreMaker starts with the sub-unfolding that contains the highest number of plates and inserts wing plate candidates at all edges that can receive them. If a wing plate has multiple edges connecting it to plates in the sub-unfolding, multiple instances of the wing plate are connected. HingeCoreMaker discards edges where the connecting wing plate overlaps with the existing plates in the sub-unfolding and scores the edges using the following four heuristics:

- Number of overlaps: the score of an edge is reduced depending on the number of overlaps with other wing plate candidates (copies of the wing plate itself are ignored).
- Folding direction of the hinge: finger hinges can only be placed along joints that fold up, and since they enable fast assembly HingeCoreMaker prefers fold-up hinges.
- Length of the edge: HingeCoreMaker prefers longer edges to enhance the sturdiness of the model during assembly.
- Number of possible connections in the next iteration: an edge is scored higher if the connected wing plate will potentially receive wing plates in the next iteration.

At each iteration of this step, HingeCoreMaker chooses the edges with the highest score as wing plate candidates and inserts the connecting plates into the sub-unfolding. The algorithm adds discarded wing plates back into the pool and the process is repeated until all available edges have been explored in the sub-unfolding(s).

HingeCoreMaker sorts the discarded wing plates (by number of edge connections) and choses a new plate to start another sub-unfolding. The process is repeated until all plates in the model have been inserted into the unfolding. At the end of the process, HingeCoreMaker pushes these changes to the UI, where the connected edges are rendered as smooth white edges on the 3D model.

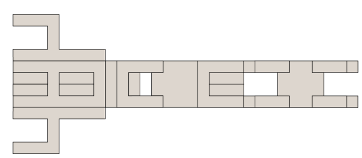

Figure 22: 2D unfolding created by HingeCoreMaker for the chair model.

Figure 22 shows the final unfolding of the chair model. While there are multiple valid assembly orders for a Hinge-Core layout, to simplify the assembly process we recommend users to start assembling at one end of the path and fold hinges until they reach the other end. If they encounter a wing plate branch, they should fold all the joints on this branch before moving along the central path.

While the HingeCoreMaker algorithm created a single unfolding of the chair model, more complex models may comprise multiple sub-unfoldings. For the example shown in Figure 23a, it is impossible to unfold the model in one piece, as the four plates in the middle part are connected to holes in the opposing plates. HingeCoreMaker detects holes in the geometry and partitions the model into three parts before creating the unfoldings. (b) In this case HingeCoreMaker was unable to connect a single plate resulting in a total of four sub-unfoldings. In case of multiple of sub-unfoldings, HingeCoreMaker indicates how they connect using pairs of engraved numbers.

To reproduce the algorithm and see the detailed structure we provide Algorithm 1 in pseudo-code.

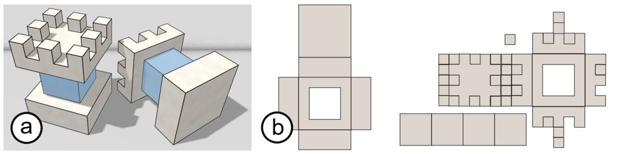

Figure 23: (a) It is impossible to edge-unfold this model due to plates connected to holes (blue). (b) HingeCoreMaker detects this and divides the model into three parts, eventually creating four sub-unfoldings.

Algorithm 1 Creating the 2D unfolding

```
create_unfolding:
Input: plates p
Output: unfolding u
// create main unfolding u*
for each pair of axes xy, xz, yz:
   strip plates s = p.filter(plate normal orthogonal to axes)
   while s is not empty:
      strip = attach all possible s
      add strip to u*
   add u* to unfoldings
u = unfolding with least sub-unfoldings and most edges
w = p.filter(plate is not in u)
// add remaining wing plates w to u
sort sub-unfoldings in u by number of edges
for each sub-unfolding su in u
   su, w = attach w to su
while w is not empty
   su = create new sub-unfolding from w with most edges
   su, w = attach w to su
return u
```

7.2 Step 2: HingeCoreMaker creates the 2D cutting plan

Finally, HingeCoreMaker generates the cutting plan, which is exported in the SVG format. HingeCoreMaker generates three types of lines as shown in Figure 9. Cut-through line (red) for each sub-unfolding, to separate it from the main sheet. This is the outline of the union of all the polygons in the sub-unfolding. Crease lines (blue) to crease each connected hinge. Partial cut lines (magenta) to create a finger joint pattern along finger hinges and disconnected edges. For hinges that fold down, only the crease line is necessary.

To program the folding angle of the finger hinges, HingeCoreMaker adjusts the gap between the finger joints. As illustrated in Figure 24a, for acute angles (<90°), the gap between the fingers is increased as the angle decreases:

$$gap = \frac{(material\ thickness\ (1 + cos\alpha\ ))}{(sin\alpha)}$$

(b) For obtuse angles (>90°), HingeCoreMaker reduces the gap by reducing the depth of fingers as the angle increases:

$$gap = material\ thickness\ (cos\ (\alpha - 90))$$

To create a sharp folded edge, HingeCoreMaker accommodates the thickness of the paper layer (1mm) and always maintains a small gap (also 1mm) between opposing joint patterns.

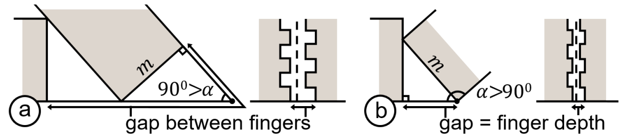

Figure 24: (a) To program angles <90°, HingeCoreMaker increases the gap. (b) For angles >90° the gap is reduced by reducing the depth of the fingers (m=material thickness).

8 TECHNICAL EVALUATION OF HINGECORE ALGORITHM

To evaluate the performance of the HingeCoreMaker algorithm, we ran HingeCoreMaker on 87 models from the Kyub repository and evaluated the results. We generated the test set by retrieving the 100 most popular models, then removing the 13 that did not have finger joints (only possessing cross-joints), resulting in 87 models for evaluation.

8.1 Results

HingeCoreMaker succeeded at creating the cutting plan for all 87 models. The average compute time for the HingeCoreMaker algorithm was 3.037 seconds (median = 2.053 seconds). Figure 25 shows the result for 7 models.

HingeCoreMaker generated fully connected layouts (single piece unfolding) for 37 models (42%). For the remaining 50 models, HingeCoreMaker succeeded at placing 87.95% of hinges of the theoretically possible number of hinges (i.e., number of plates in the model − 1). Note that sub-unfoldings created preemptively by HingeCoreMaker due to geometry which is impossible to edge-unfold (e.g., plates connected to holes) are ignored for this metric. As illustrated by Figure 25, processing times ranged from 2-9 seconds.

Overall, our technical evaluation shows (1) that our implementation is robust, (2) that the algorithm is fast, i.e., does not add significant time to the laser cutting pipeline, and (3) that the resulting layouts are highly connected, which maximizes assembly speed.

9 USER STUDY ON ASSEMBLY SPEED

To validate our claim that HingeCore can speed up the assembly process, we ran a user study in which each participants assembled one copy of the chair model shown in Figure 1 created using HingeCoreMaker and one created using the state-of-the-art for fast assembly Roadkill [1]. We used a within-subjects' design and participants assembled models in counterbalanced order. We hypothesized that participants would assemble the model faster in the HingeCore condition.

9.1 Interface conditions

There were two interface conditions. In the HingeCore condition a 2D folding layout was generated using the Hinge CoreMaker algorithm presented in this paper (see Figure 1). Polyurethane based foamcore is used with the residue removed prior to conducting the user study. In the Roadkill condition 2D layouts were generated using the Roadkill algorithm presented in [1].

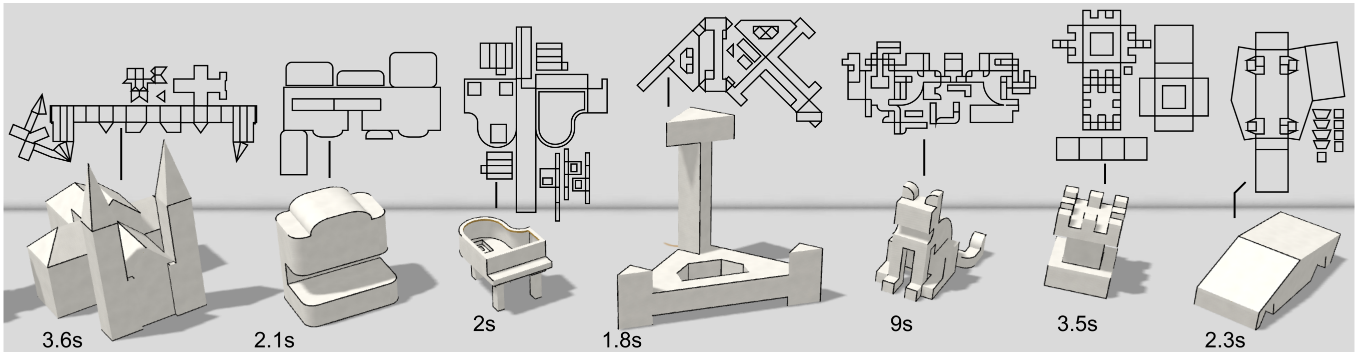

Figure 25: HingeCore layouts of seven test models.

9.2 Task & Procedure

Participants performed two trials (within-subject design). During each trial, participants assembled one chair model, as shown in Figure 1 (23 plates). In the HingeCore trial, the model was made from 5mm Foamcore, in the Roadkill condition from 4mm plywood. The study was counterbalanced, so that half of the participants started with the HingeCore model, while the other half started with the Roadkill model.

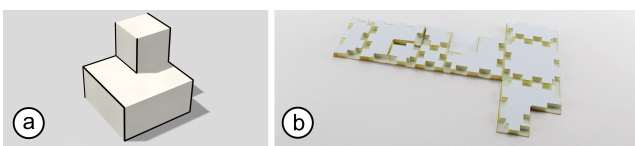

Figure 26: (a) Models and (b) layout used to train the participants for the HingeCore interface.

Before performing each trial, participants viewed a training video, which showed how to assemble simple objects using the HingeCoreMaker interface at the example of a simplified object (Figure 26) (1:38 minute for HingeCore, 2:40 minute for Roadkill). Participants also physically assembled the training models after watching the video.

After completing all conditions, participants filled in a questionnaire. All participants finished the study within 30 mins.

9.3 Participants

We recruited 12 participants (7 male, 5 female, average age = 24.3) from our institution. None of the participants had any previous experience with assembling laser-cut objects.

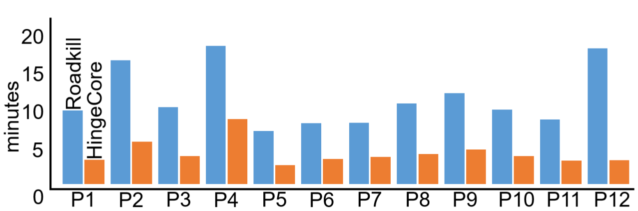

Figure 27: Results: The average assembly time for the HingeCore interface was 2.9x faster than Roadkill.

9.4 Results

Completion time: Figure 27 illustrates the assembly times for all participants. As expected, participants spent less time assembling the HingeCore layout, 4:15 mins on average, while an average of 11:56 mins were spent on assembling the Roadkill layout. Differences were significant ($t(11) = 8.292$, $p < 0.001$, $d = 2.394$) and the effect was substantial: average assembly time was 2.9x faster in the HingeCore condition.

Subjective feedback: The results of the questionnaire are shown in Figure 28. For the HingeCore layout, participants rated the process of finding and folding the hinges as "easy". Overall, the participants enjoyed assembling both the layouts. The biggest strength of HingeCore compared to Roadkill was that participants found it "easy" to align and join multiple parts at the same time.

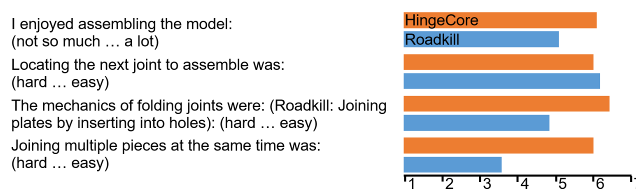

Figure 28: The results of the post-study questionnaire.

Figure 29 shows the results of four additional HingeCore-specific questions. All participants rated finding the folding direction as "easy" with P3 saying "even if you get stuck you can continue easily". All participants noted that the finger hinges "worked nicely" with P6 mentioning "folding the parts was satisfying". While 6 of the participants never undid a hinge (thus answered N/A to that question), participants who had to do it found it "easy" with P4 undoing more than half the model during the assembly.

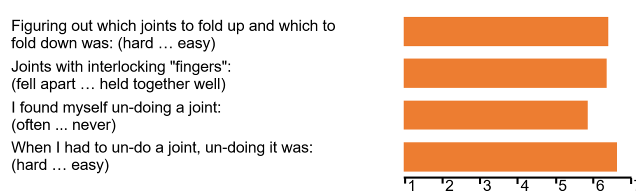

Figure 29: The results of the questions asked specifically for the HingeCore interface.

9.5 Qualitative results

We observed that making mistakes while folding HingeCore was less costly compared to the baseline. The reason was that whenever a participant had to reverse a step, they were easily able to undo the hinges and the plate would remain connected in its place for later assembly. However, for the Roadkill layout, taking out the plate was difficult in the first place and as soon as the plate was removed the participants could easily forget its position and orientation in the model.

Another factor was that single cut “fold down” hinges do not maintain their folding angle. We observed participants being confused when encountering these hinges. This reinforces the heuristic that HingeCoreMaker prefers to place fold up finger hinges (see Section "Algorithm"), as they maintain angle and position, rather than simple fold down hinges.

9.6 Discussion

In our study, participants assembled HingeCore models 2.9x faster than Roadkill models. This confirms our hypothesis that HingeCore speeds up assembly.

While folding single pieces was faster in the HingeCore condition, joining multiple pieces at once turned out to be the biggest distinguishing factor. This effect was also noted in the questionnaire, with participants rating Roadkill as “hard” compared to HingeCore. The reason HingeCore performed better is that the foam layer in HingeCore layouts is more compliant than plywood, allowing participants to mount these plates using less force.

We did not include multi-part models in the study as in our observation, multi-part models do not take significantly longer than single-part models, such as the chair model explored in this study. This effect has been previously explained in the related work Roadkill [1]. As the authors of Roadkill explain, assembling multiple parts requires a time effort of O(n2) in the number of parts. However, and that is the main contribution of Roadkill, they bring down the number of parts by a factor of 5.5 (81% connectivity), and that reduces visual search by 5.52 = 30, making it negligible. With HingeCore, we bring the number of parts down by a similar factor of 8.1 (87.95% connectivity, i.e., each part consists of 8.1 plates on average), so the effort of putting together multi-part models is reduced by a factor of 8.12 = 65. This matches our observation during various pilots with multi-part models, in which the effect of visual search was always minor. Based on this, we considered it unnecessary to include multi-part models in the study.

In addition to participants being faster in the HingeCore condition, they also seemed to have an easier time assembling that model. This is expected as HingeCore (1) largely eliminates the necessity to locate and arrange parts (similar to Roadkill [1]), (2) can be assembled with less force than rigid materials (see Section “HingeCore”), and (3) because parts stay put during assembly.

To explore these particular qualities, we collected one additional bit of anecdotal evidence by asking an elementary school child (female, age = 7) to assemble the HingeCore layout of the chair model. As shown in Figure 30, she completed the task successfully and without help. Her task completion time (5:16 mins) was even comparable to the adult participants of the study reported above. This observation encourages us to further research HingeCore as a means of bringing laser-cutting to younger children.

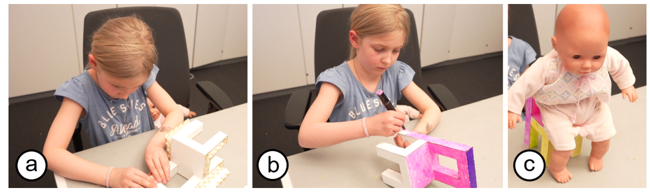

Figure 30: (a) Assembling HingeCore layouts does not require finding parts and requires little physical force. This allowed our 7-year-old test participant to assembly this chair by herself. (b) The clean white HingeCore surfaces afford coloring, while (c) their sturdiness allows for active play.

10 CONCLUSION AND FUTURE WORK

In this paper, we presented HingeCore, a novel laser-cut 3D structure made from foamcore that allows for very fast assembly, while also resulting in sturdy objects.

By advancing fast assembly, HingeCore also advances fast laser cutting as a whole. In the case of the chair used in the study, the 2.9x faster assembly amounts to a considerable 37% speed-up of the entire design-cut-assemble process.

We anticipate use primarily in domains where speed is crucial, such as physical prototyping within design sessions or personal fabrication in the highly restrictive timeframe set by schools, but also in industrial design and architecture, because of the sturdy results, while maintaining a clean look.

As future work, we are planning to explore additional application scenarios, such as physical prototyping with younger kids, where HingeCore's particular ease of assembly should be impactful.

ACKNOWLEDGMENTS

We thank Philippa Baudisch for assembling the chair for us and for lots of painted unicorns.

REFERENCES

[1] Muhammad Abdullah, Romeo Sommerfeld, Laurenz Seidel, Jonas Noack, Ran Zhang, Thijs Roumen and Patrick Baudisch. “Roadkill: Nesting laser-cut objects for fast assembly.” In Proceedings of the 34th annual ACM symposium on User interface software and technology (UIST '21).

[2] Muhammad Abdullah, Martin Taraz, Yannis Kommana, Shohei Katakura, Robert Kovacs, Jotaro Shigeyama, Thijs Roumen, and Patrick Baudisch. "FastForce: Real-Time Reinforcement of Laser-Cut Structures." In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, pp. 1-12. 2021.

[3] Zachary Abel, and Erik D. Demaine. "Edge-Unfolding Orthogonal Polyhedra is Strongly NP-Complete." In CCCG. 2011.

[4] Harshit Agrawal, Udayan Umapathi, Robert Kovacs, Johannes Frohnhofen, Hsiang-Ting Chen, Stefanie Mueller, and Patrick Baudisch. "Protopiper: Physically sketching room-sized objects at actual scale." In Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology, pp. 427-436. 2015.

[5] Byoungkwon An, Ye Tao, Jianzhe Gu, Tingyu Cheng, Xiang 'Anthony' Chen, Xiaoxiao Zhang, Wei Zhao, Youngwook Do, Shigeo Takahashi, Hsiang-Yun Wu, Teng Zhang, and Lining Yao. 2018. Thermorph: Democratizing 4D Printing of Self-Folding Materials and Interfaces. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18). Association for Computing Machinery, New York, NY, USA, Paper 260, 1–12. DOI:https://doi.org/10.1145/3173574.3173834

[6] Patrick Baudisch and Stefanie Mueller. "Personal fabrication." Foundations and Trends in Human-Computer Interaction 10, no. 3-4 (2016): 165-293.

[7] Patrick Baudisch, Arthur Silber, Yannis Kommana, Milan Gruner, Ludwig Wall, Kevin Reuss, Lukas Heilman, Robert Kovacs, Daniel Rechlitz, and Thijs Roumen. 2019. Kyub: A 3D Editor for Modeling Sturdy Laser-Cut Objects. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19). ACM, New York, NY, USA, Paper 566, 12 pages. DOI: https://doi.org/10.1145/3290605.3300796

[8] Dustin Beyer, Serafima Gurevich, Stefanie Mueller, Hsiang-Ting Chen, and Patrick Baudisch. 2015. Platener: Low-Fidelity Fabrication of 3D Objects by Substituting 3D Print with Laser-Cut Plates. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15). Association for Computing Machinery, New York, NY, USA, 1799–1806. DOI:https://doi.org/10.1145/2702123.2702225

[9] CGAL, https://www.cgal.org, last accessed April 2022.

[10] Ruei-Che Chang, Chih-An Tsao, Fang-Ying Liao, Seraphina Yong, Tom Yeh, and Bing-Yu Chen. "Daedalus in the Dark: Designing for Non-Visual Accessible Construction of Laser-Cut Architecture." In Proceedings of the 34th Annual ACM Symposium on User Interface Software and Technology, 2021.

[11] Lujie Chen, and Lawrence Sass. "Fresh press modeler: A generative system for physically based low fidelity prototyping." Computers & Graphics 54 (2016): 157-165.

[12] Mirela Damian, Robin Flatland, and Joseph O'Rourke. "Epsilon-unfolding orthogonal polyhedra." Graphs and Combinatorics 23, no. 1 (2007): 179-194.

[13] Erik D. Demaine, and Joseph O'Rourke. "A survey of folding and unfolding in computational geometry." Combinatorial and computational geometry 52 (2005): 167-211.

[14] Steven P. Dow, Kate Heddleston, and Scott R. Klemmer. "The efficacy of prototyping under time constraints." In Proceedings of the seventh ACM conference on Creativity and cognition, pp. 165-174. 2009.

[15] Fusion 360 Slicer, https://www.autodesk.com/products/fusion-360/, last accessed April 2022.

[16] Daniel Groeger, and Jürgen Steimle. "Lasec: Instant fabrication of stretchable circuits using a laser cutter." In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, pp. 1-14. 2019.

[17] Björn Hartmann, Scott R. Klemmer, Michael Bernstein, Leith Abdulla, Brandon Burr, Avi Robinson-Mosher, and Jennifer Gee. "Reflective physical prototyping through integrated design, test, and analysis." In Proceedings of the 19th annual ACM symposium on User interface software and technology, pp. 299-308. 2006.

[18] Florian Heller, Jan Thar, Dennis Lewandowski, Mirko Hartmann, Pierre Schoonbrood, Sophy Stönner, Simon Voelker, and Jan Borchers. 2018. CutCAD - An Open-source Tool to Design 3D Objects in 2D. In Proceedings of the 2018 Designing Interactive Systems Conference (DIS '18). Association for Computing Machinery, New York, NY, USA, 1135–1139. DOI:https://doi.org/10.1145/3196709.3196800

[19] Yue Hao, Yun-hyeong Kim, and Jyh-Ming Lien. "Synthesis of fast and collision-free folding of polyhedral nets." In Proceedings of the 2nd ACM Symposium on Computational Fabrication, pp. 1-10. 2018.

[20] Martin Kilian, Aron Monszpart, and Niloy J. Mitra. 2017. String actuated curved folded surfaces. ACM Trans. Graph. 36, 3, Article 25 (May 2017).

[21] Jason S. Ku, and Erik D. Demaine. "Folding flat crease patterns with thick materials." Journal of Mechanisms and Robotics 8, no. 3 (2016): 031003.

[22] Robert J. Lang, Origami design secrets: mathematical methods for an ancient art. CRC Press, 2012.

[23] Danny Leen, Tom Veuskens, Kris Luyten, and Raf Ramakers. "JigFab: Computational fabrication of constraints to facilitate woodworking with power tools." In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, pp. 1-12. 2019.

[24] Danny Leen, Nadya Peek, and Raf Ramakers. "LamiFold: Fabricating Objects with Integrated Mechanisms Using a Laser cutter Lamination Workflow." In Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology, pp. 304-316. 2020.

[25] Honghua Li, Ruizhen Hu, Ibraheem Alhashim, and Hao Zhang. "Foldabilizing furniture." ACM Trans. Graph. 34, no. 4 (2015): 90-1.

[26] Minchen Li, Danny M. Kaufman, Vladimir G. Kim, Justin Solomon, and Alla Sheffer. "Optcuts: Joint optimization of surface cuts and parameterization." ACM Transactions on Graphics (TOG) 37, no. 6 (2018): 1-13.

[27] Min Liu, Yunbo Zhang, Jing Bai, Yuanzhi Cao, Jeffrey M. Alperovich, and Karthik Ramani. "WireFab: Mix-Dimensional Modeling and Fabrication for 3D Mesh Models." In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, pp. 965-976. 2017.

[28] Hiroshi Masuda. "Topological operators and Boolean operations for complex-based nonmanifold geometric models." Computer-Aided Design 25, no. 2 (1993): 119-129.

[29] James McCrae, Nobuyuki Umetani, and Karan Singh. 2014. FlatFitFab: interactive modeling with planar sections. In Proceedings of the 27th annual ACM symposium on User interface software and technology (UIST '14). Association for Computing Machinery, New York, NY, USA, 13–22. DOI:https://doi.org/10.1145/2642918.2647388

[30] Jun Mitani, and Hiromasa Suzuki. "Making papercraft toys from meshes using strip-based approximate unfolding." ACM transactions on graphics (TOG) 23, no. 3 (2004): 259-263.

[31] Stefanie Mueller, Sangha Im, Serafima Gurevich, Alexander Teibrich, Lisa Pfisterer, François Guimbretière, and Patrick Baudisch. "WirePrint: 3D printed previews for fast prototyping." In Proceedings of the 27th annual ACM symposium on User interface software and technology, pp. 273-280. 2014.

[32] Stefanie Mueller, Tobias Mohr, Kerstin Guenther, Johannes Frohnhofen, and Patrick Baudisch. "faBrickation: fast 3D printing of functional objects by integrating construction kit building blocks." In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 3827-3834. 2014.

[33] Alessandro Muntoni, Stefano Nuvoli, Andreas Scalas, Alessandro Tola, Luigi Malomo, and Riccardo Scateni. "Mill and fold: Shape simplification for fabrication." Computers & Graphics 80 (2019): 17-28.

[34] Martin Nisser, Christina Liao, YuChen Chai, Aradhana Adhikari, Steve Hodges, and Stefanie Mueller. " LaserFactory: A Laser Cutter-based Electromechanical Assembly and Fabrication Platform to Make Functional Devices & Robots" In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 2021.

[35] James Noeckel, Haisen Zhao, Brian Curless, and Adriana Schulz. "Fabrication-Aware Reverse Engineer-ing for Carpentry." In Computer Graphics Forum, vol. 40, no. 5, pp. 301-314. 2021.

[36] Yuta Noma, Koya Narumi, Fuminori Okuya, and Yoshihiro Kawahara. "Pop-up Print: Rapidly 3D Printing Mechanically Reversible Objects in the Folded State." In Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology, pp. 58-70. 2020.

[37] Simon Olberding, Sergio Soto Ortega, Klaus Hildebrandt, and Jürgen Steimle. "Foldio: Digital fabrication of interactive and shape-changing objects with foldable printed electronics." In Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology, pp. 223-232. 2015.

[38] Joseph O'Rourke. "Unfolding orthogonal polyhedra." Contemporary Mathematics 453 (2008): 307-318.

[39] Keunwoo Park, Conrad Lempert, Muhammad Abdullah, Shohei Katakura, Jotaro Shigeyama, Thijs Roumen and Patrick Baudisch. " FoolProofJoint: Reducing Assembly Errors of Laser Cut 3D Models by Means of Custom Joint Patterns." In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems.

[40] Huaishu Peng, Rundong Wu, Steve Marschner, and François Guimbretière. "On-the-fly print: Incremental printing while modelling." In Proceedings of the 2016 CHI conference on human factors in computing systems, pp. 887-896. 2016.

[41] Varun Perumal, and Daniel J. Wigdor. "Foldem: Heterogeneous Object Fabrication via Selective Ablation of Multi-Material Sheets." In CHI, pp. 5765-5775. 2016.

[42] A. E. Ranger, and L. F. Hopkins. "A new theory of the tensile behaviour of paper." In The Formation and Structure of Paper-Transactions of the Symposium held at Oxford, September 1961, pp. 277-318. 1962.

[43] Nicolas Rogeau, Pierre Latteur, and Yves Weinand. "An integrated design tool for timber plate structures to generate joints geometry, fabrication toolpath, and ro-bot trajectories." Automation in Construction 130 (2021): 103875.

[44] Thijs Roumen, Ingo Apel, Jotaro Shigeyama, Abdullah Muhammad, and Patrick Baudisch. "Kerf-canceling mechanisms: making laser-cut mechanisms operate across different laser cutters." In Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology, pp. 293-303. 2020.

[45] Thijs Roumen, Yannis Kommana, Ingo Apel, Conrad Lempert, Markus Brand, Erik Brendel, Laurenz Seidel, Lukas Rambold, Carl Goedecken, Pascal Crenzin, Ben Hurdelhey, Muhammad Abdullah, and Patrick Baudisch. "Assembler3: 3D Reconstruction of Laser-Cut Models." In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, pp. 1-11. 2021.

[46] Thijs Roumen, Conrad Lempert, Ingo Apel, Erik Brendel, Markus Brand, Laurenz Seidel, Lukas Rambold, and Patrick Baudisch. "AutoAssembler: Automatic Reconstruction of Laser-Cut 3D Models" In Proceedings of the 34th annual ACM symposium on User interface software and technology (UIST '21).

[47] Madlaina Signer, Alexandra Ion, and Olga Sorkine-Hornung. 2021. Developable Metamaterials: Mass-fabricable Metamaterials by Laser-Cutting Elastic Structures. In CHI Conference on Human Factors in Computing Systems (CHI '21), May 8–13, 2021, Yokohama, Japan. ACM, New York, NY, USA 13 Pages.

[48] Hanieh Shakeri, Hannah Elbaggari, Paul Bucci, Robert Xiao, and Karon E. MacLean. "FoldMold: Automating Papercraft for Fast DIY Casting of Scalable Curved Shapes." In Graphics Interface 2021. 2020.

[49] Evgeny Stemasov, Enriko Rukzio and Jan Gugenheimer, "The Road to Ubiquitous Personal Fabrication: Modeling-Free Instead of Increasingly Simple," in IEEE Pervasive Computing, vol. 20, no. 1, pp. 19-27, 1 Jan.-March 2021, DOI: https://10.1109/MPRV.2020.3029650

[50] Evgeny Stemasov, Alexander Botner, Enrico Rukzio, and Jan Gugenheimer. 2022. Ephemeral Fabrication: Exploring a Ubiquitous Fabrication Scenario of Low-Effort, In-Situ Creation of Short-Lived Physical Artifacts. In Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '22). Association for Computing Machinery, New York, NY, USA, Article 25, 1–17.

[51] Raphael Straub, and Hartmut Prautzsch. Creating optimized cut-out sheets for paper models from meshes. KIT, Fakultät für Informatik, 2011.

[52] Hyunyoung Song, François Guimbretière, Chang Hu, and Hod Lipson. "ModelCraft: capturing freehand annotations and edits on physical 3D models." In Proceedings of the 19th annual ACM symposium on User interface software and technology, pp. 13-22. 2006.

[53] Tomohiro Tachi. "Rigid-foldable thick origami." Origami 5, no. 5 (2011): 253-264.

[54] Shigeo Takahashi, Hsiang-Yun Wu, Seow Hui Saw, Chun-Cheng Lin, and Hsu-Chun Yen. "Optimized topological surgery for unfolding 3d meshes." In Computer graphics forum, vol. 30, no. 7, pp. 2077-2086. Oxford, UK: Blackwell Publishing Ltd, 2011.

[55] Trotec speedy 360 laser cutter, https://www.troteclaser.com/, last accessed April 2022.

[56] Michael T. Tolley, *et al.* "Self-folding origami: shape memory composites activated by uniform heating." Smart Materials and Structures 23.9 (2014): 094006.

[57] Tom Valkeneers, Danny Leen, Daniel Ashbrook, and Raf Ramakers. "StackMold: Rapid Prototyping of Functional Multi-Material Objects with Selective Levels of Surface Details." In Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology, pp. 687-699. 2019.

[58] Ziqi Wang, Peng Song, and Mark Pauly. "State of the art on computational design of assemblies with rigid parts." In Computer Graphics Forum, vol. 40, no. 2, pp. 633-657. 2021.

[59] Zhujiang Wang, Zimo Wang, Woo-Hyun Ko, Ashif Sikandar Iquebal, Vu Nguyen, Nazanin Afsar Kazerooni, Qiyang Ma, Arun Srinivasa, Panganamala Ramana Kumar, and Satish Bukkapatnam. "An autonomous laser kirigami method with low-cost real-time vision-based surface deformation feedback system." The International Journal of Advanced Manufacturing Technology 118, no. 5 (2022): 1873-1883.

[60] Xiangzhi Wei, Siqi Qiu, Lin Zhu, Ruiliang Feng, Yaobin Tian, Juntong Xi, and Youyi Zheng. "Toward support-free 3D printing: A skeletal approach for partitioning models." Ieee Transactions on visualization and computer graphics 24, no. 10 (2017): 2799-2812.

[61] Katja Wolff, Roi Poranne, Oliver Glauser, and Olga Sorkine-Hornung. "Packable springs." In Computer Graphics Forum, vol. 37, no. 2, pp. 251-262. 2018.

[62] Chenming Wu, Haisen Zhao, Chandrakana Nandi, Jeffrey I. Lipton, Zachary Tatlock, and Adriana Schulz. "Carpentry compiler." ACM Transactions on Graphics (TOG) 38, no. 6 (2019): 1-14.

[63] Zhonghua Xi, Yun-Hyeong Kim, Young J. Kim, and Jyh-Ming Lien. "Learning to segment and unfold polyhedral mesh from failures." Computers & Graphics 58 (2016): 139-149.

[64] Zhonghua Xi, and Jyh-Ming Lien. "Polyhedra Fabrication Through Mesh Convexification: A Study of Foldability of Nearly Convex Shapes." In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, vol. 58189, p. V05BT08A034. American Society of Mechanical Engineers, 2017.

[65] Junichi Yamaoka, Mustafa Doga Dogan, Katarina Bulovic, Kazuya Saito, Yoshihiro Kawahara, Yasuaki Kakehi, and Stefanie Mueller. "FoldTronics: Creating 3D objects with integrated electronics using foldable honeycomb structures." In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, pp. 1-14. 2019.

[66] Junichi Yamaoka, and Yasuaki Kakehi. "ProtoMold: An interactive vacuum forming system for rapid prototyping." In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, pp. 2106-2115. 2017.

[67] Clement Zheng, Ellen Yi-Luen Do, and Jim Budd. 2017. Joinery: Parametric Joint Generation for Laser Cut Assemblies. In Proceedings of the 2017 ACM SIGCHI Conference on Creativity and Cognition (C&C '17). Association for Computing Machinery, New York, NY, USA, 63–74. DOI:https://doi.org/10.1145/3059454.3059459