# LamiFold: Fabricating Objects with Integrated Mechanisms Using a Laser cutter Lamination Workflow

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## ABSTRACT
We present LamiFold, a novel design and fabrication workflow for making functional mechanical objects using a laser cutter. Objects fabricated with LamiFold embed advanced rotary, linear, and chained mechanisms, including linkages that support fine-tuning and locking position. Laser cutting such mechanisms without LamiFold requires designing for and embedding off-the-shelf parts such as springs, bolts, and axles for gears. The key to laser cutting our functional mechanisms is the selective cutting and gluing of stacks of sheet material. Designing mechanisms for this workflow is non-trivial, therefore we contribute a set of mechanical primitives that are compatible with our lamination workflow and can be combined to realize advanced mechanical systems. Our software design environment facilitates the process of inserting and composing our mechanical primitives and realizing functional laser-cut objects.

## Author Keywords
Personal Fabrication; Lamination; Mechanical Design; CAD

## CCS Concepts
**•Human-centered computing → Interactive systems and tools; •Applied computing → Computer-aided manufacturing;**

## INTRODUCTION
Both CO2 laser cutters and 3D printers are highly popular digital fabrication machinery for prototyping objects. Both types of machines have strengths and weaknesses: while laser cutting is often faster compared to 3D printing, the latter produces more intricate 3D shapes [18]. One important class of objects, challenging to produce with laser cutters, are those that embed functional mechanisms, such as springs, bolts, or axles for gears or wheels [5]. These mechanical parts cannot be produced with traditional laser cutting machines and therefore require manual assembly of laser cut parts and off-the-shelf mechanical parts. Besides the additional assembly steps, the integration of mechanical parts complicates the design of laser cut objects as one needs to select and buy appropriate parts and fit the mechanical design to sizes and tolerances of those items. Such mechanical designs also require further adjustments when scaling the design or when producing the same artifact in countries having different standards, such as metric

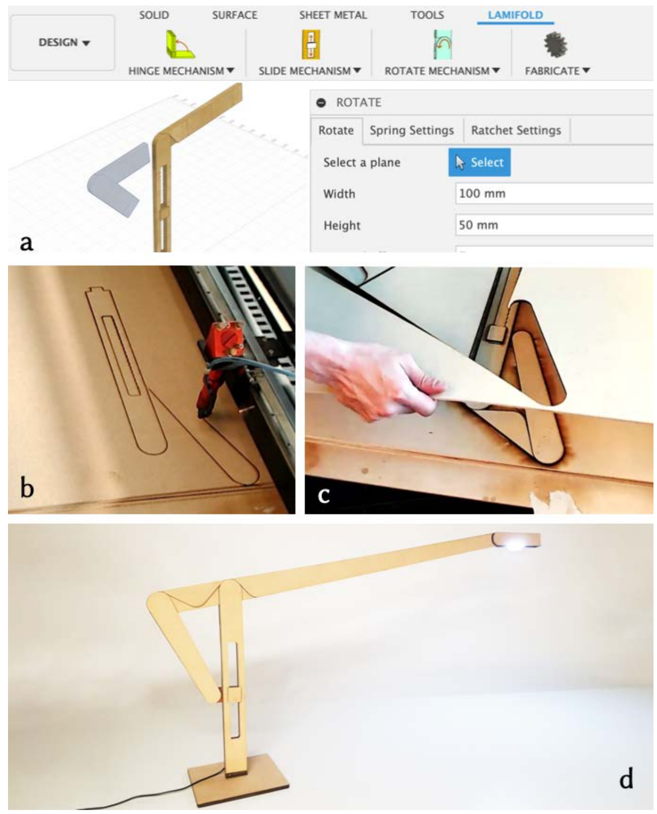


**Figure 1. LamiFold's streamlined workflow: (a) Designing a desk lamp using LamiFold mechanisms, (b) Laser cutting sheet material using the custom generated glue and contour files, (c) Removing outer layers from the lamination stack revealing the object, (d) Folding up a ready to use desk lamp with embedded mechanism.**


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vs. inches units or ISO threads vs. pipe threads. In contrast, many 3D printing technologies, such as FDM, support printing intricate mechanical parts, such as springs and threads inside objects. As these mechanical parts are digitally designed, they can adjust and scale to fit the model. Hence, mechanisms embedded in 3D prints are immediately functional after removing support material, and no assembly is needed [10, 16].

To empower designers to fabricate functional mechanisms using laser cutters, we introduce a novel set of laser cutter compatible primitives for frequently used mechanisms, such as rotating (revolute) and sliding (prismatic) joints. The design of our primitives embed features, such as constraining and locking moving elements, which traditionally require embedding off-the-shelf mechanical parts. The key to our approach is to construct three-dimensional objects and functional mechanisms by selectively laser cutting and gluing stacks of sheet material, an approach often referred to as sheet lamination [22]. While sheet lamination using laser cutters has been explored to selectively adhere sheets of acrylic [33] and to avoid assembly of micro-scale objects [37, 38], LamiFold's lamination approach is compatible with a wide variety of sheet materials and allows for making desktop-size functional objects.

In this paper, we present *LamiFold*, a design and fabrication technique for laser cutting functional three-dimensional objects with embedded mechanisms, such as the swing arm desk lamp shown in Figure 1d. LamiFold achieves this by offering a software design environment that allows users to combine and customize laser cut mechanical primitives (Figure 1.a). After testing and fine-tuning a mechanical object in software, the LamiFold software environment folds the functional 3D object to a 2D lamination stack, ready for fabrication using a CO2 laser cutter. LamiFold's streamlined fabrication workflow consists of laser cutting and selectively gluing layers (Figure 1.b). The final laminated stack folds into the 3D object and embeds all functional mechanisms to operate the lamp (Figure 1.c-d). Functional objects fabricated with LamiFold can be used and exposed as design elements and allow for user and functional testing to gather insights for future design iterations. While 3D printing this swing arm desk lamp would be impractical in its current shape, laser cutting this object without LamiFold would require manual assembly steps and adapting the design to fit and work with off-the-shelf mechanical parts.

LamiFold offers an end-to-end design and fabrication workflow that empowers designers to laser cut functional mechanical objects. More specifically, we contribute:

1. An extensive set of parametric mechanical primitives that can be fabricated with laser cutter and sheet lamination.

2. A streamlined sheet lamination workflow for fabricating 3D objects with embedded mechanisms using a laser cutter.

3. A software environment that supports designers in making functional laser-cut mechanisms by customizing, combining, and embedding our mechanical primitives.

## WALKTHROUGH

This walkthrough gives an overview of LamiFold's design and fabrication workflow while making a functional swing arm desk lamp. The LamiFold design environment is implemented as a plugin for Autodesk Fusion 360 [8], a popular and widespread CAD environment. This plugin offers features for adding, configuring, and simulating the workings of LamiFold mechanical primitives. At any time, the user can use standard Fusion 360 modeling features to adjust and combine mechanical primitives further and realize a desired functional object. LamiFold proposes an iterative design process in which users switch between designing and fine-tuning the functional object (Step 1) and testing its functionality (Step 2).

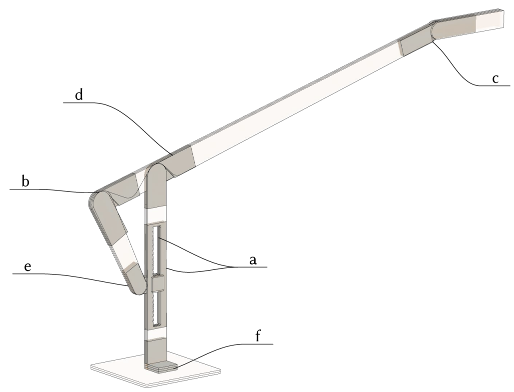


**Figure 2. Drawing of the desk lamp showing the embedded LamiFold mechanisms. (a) Two sliding mechanisms, (b,c,d,e) Four rotating mechanisms, (f) One hinge mechanism.**

### Step 1: Designing a swing arm desk lamp

Figure 2 shows the conceptual design of a desk lamp consisting of four rotating mechanisms, two sliding mechanisms, and one hinge mechanism.

The user starts by inserting two sliding mechanisms in LamiFold's design environment (Figure 3.a). Simple dialog boxes allow for configuring the dimensions as well as the internal mechanism. For this mechanism, the user selects a ratchet mechanism with an additional release button to allow for adjusting the height of the lamp and locking its current position. The mechanism is further fine-tuned using standard modeling operations in Fusion 360. Figure 3.b shows how the overlapping knob elements of two sliding mechanisms are merged using the *combine* operation in Fusion 360. The two mechanisms now move together and reinforce each other.

The design process continues by adding, configuring, and combining the four rotating mechanisms of the desk lamp. In Figure 4.a the user configures the rotating mechanism for

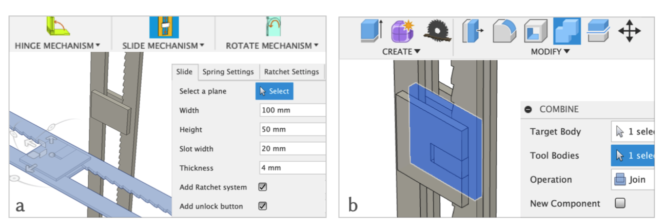


**Figure 3. LamiFold interface (a) Adding sliding mechanisms, (b) Merging elements using the combine operation.**

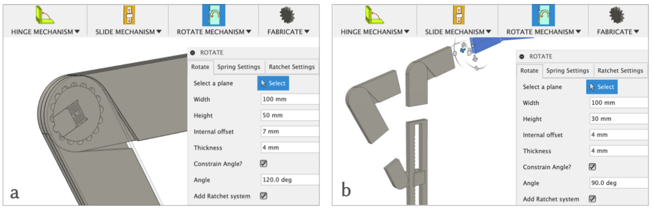


**Figure 4. LamiFold design environment, adding rotating mechanisms.**

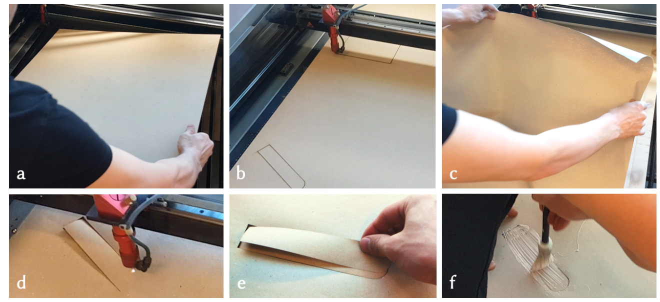


**Figure 6. The Lamifold laser cutter fabrication workflow.**

the elbow joint in the back of the desk lamp (Figure 2.b) by selecting a ratchet as the internal mechanism and limiting the range of movement.

In contrast, the upper joint (Figure 4.b) in the head of the desk lamp consists of a ratchet mechanism with an embedded release button to point the lamp in different directions (Figure 2.c). The other two rotating mechanisms (Figure 2.d and 2.e) are basic pivot points and move along with the connected linkages. After adding and combining several mechanisms, the composed functionality is to be tested and fine-tuned in software (Step 2).

The final design step involves adding a hinge joint for the base of the desk lamp. This hinge joint pivots out-of-plane and ensures that the base panel is positioned perpendicular to other linkages. A custom-designed base plate is attached to the hinge mechanism by combining the bottom layer of the mechanism and the base plate in a *rigid group*.

### Step 2: Simulating the mechanical functionality

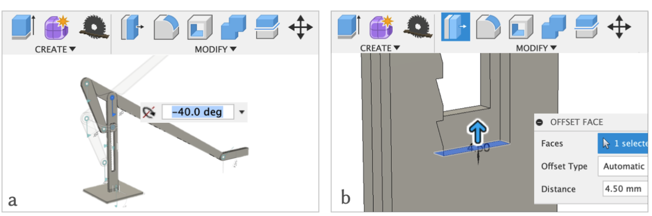


**Figure 5. Testing and fine-tuning the mechanisms of the desk lamp in software.**

LamiFold mechanisms can be tested in software at any time in the design process. When mechanisms are active (double click), simple direct manipulation controls allow for manipulating mechanisms within the valid ranges. In Figure 5.a, the user controls the sliding movement and observes the effect of the connected linkages. Moving the swing arm desk lamp to the minimum and maximum angles makes it convenient to adjust the start and end stops of slots in the sliding mechanisms using basic *push/pull* operations (Figure 5.b).

### Step 3: Fabricating the desk lamp

Once the user is satisfied with the design our software folds the 3D object into a stack of laminated sheets and exports different vector graphics files for the laser cutting process. The fabrication process starts with laser cutting the first layer of MDF material (Figure 6.a-b).

Next, the layer is covered with paper which is fixed in place with scotch tape. After laser processing (Figure 6.c), this paper layer serves as a stencil for the selective application of glue (Figure 6.d-e). After applying wood glue with a large brush (Figure 6.f), the user adds the next layer of MDF material to the stack and starts processing the second layer. After laser cutting every layer of sheet material, an engraved hatch pattern shows the user which parts to take out before proceeding with the next layer. When all six layers are laminated, the excess material surrounding the contour of the desk lamp is removed, leaving a single laminated stack behind.

### Step 4: Folding and Assembly

Once the glue is cured (Figure 7.a), the user folds the hinge mechanism. This hinge joint has an embedded locking mechanism that permanently locks the desk lamp into its 3D configuration (Figure 7.b). The desk lamp is augmented with electronics and can be used and exposed as a design element (Figure 7.c-d). Alternatively, the design can be used as a functional test for further design iterations.


**Figure 7. Folding the desk lamp.**

## RELATED WORK

Fabricating objects by laminating sheets is an ancient technique: there are examples that go backs early as ancient Egypt [4], where laminated wood veneer was used to create objects. Folding sheets to create 3D structures is similarly historic and has been practiced as origami as early as the 8th century [4].

These traditional crafts techniques have inspired many engineering applications ranging from the building-scale [31] to the microscopic [26].

More recently, digital fabrication tools such as laser cutters and 3D printers have made fabricating such objects more accessible. CAD and computer-controlled fabrication tools make creating complex geometries easier and more repeatable. This has provided an opportunity for HCI researchers to engage users in fabrication practices that previously required extensive craft skill [42] or develop novel workflows that blend digital fabrication and traditional craft techniques, for example to make complex joints [15]. Furthermore, this has created an opportunity for HCI researchers to use these fabrication techniques when creating novel devices and systems. However, further research is needed in developing software and fabrication tools that support users in creating complex 3D objects. Either it is hard for non-experts to know how to create a geometry that allows for certain degrees of movement (e.g. a disc connecting two parts that can turn with respect to each other), or the fabrication tools require post-processing steps like manual assembly, which is cumbersome and error-prone.

Fabricating objects with stacked and laminated cut paper has been used as a commercial 3D printing technique by companies including Mcor and Helisys. HCI researchers have used such printers to create novel devices by embedding paper electronics [21, 25]; adapted stacking fabrication techniques to thicker plastic and plywood sheets for more rapid prototyping [33]; adapted them to fabric for creating soft goods [24]; combined stacking with folding to quickly create large complex shapes [18]; and used stacking techniques to produce tooling to cast parts [34].

Beyond static objects, lamination and folding techniques can also be used to create moving parts. Pop-up cards are a well-known application of laminated and folded mechanisms. Creating pop-up structures requires ingenuity and relies on a variety of fabrication techniques. In graphics and geometry processing, Li et al. provide a categorization of techniques for making pop-up structures in [14]. Xiao et al. have developed computational methods of designing pop-up structures in [39], with Ruiz et al. implementing pop-up structures with multiple mechanisms [29]. Folding and pop-up structures such as these enable the rapid assembly of complex structures, which is of particular value if the assembly process needs to be limited in size or cost. By using pop-up techniques together with microfabrication, researchers have even been able to fabricate insect-sized robots that are immediately functional and require no post-fabrication assembly steps [36, 1]. Beyond small size, print-and-fold robotics [17] make the fabrication and assembly of robots extremely low-cost, which in turn enables roboticists to explore a wide range of locomotive robots [30]. The Cardboard Machine Kit uses folding and lamination to create frames for exploring a wide range of rapid prototyping machines [23]. Lamifold seeks to similarly facilitate the exploration of making objects with moving parts.

HCI researchers have contributed end-user systems to make exploring different design patterns that these fabrication techniques and mechanisms afford accessible. FoldMecha is for example an end-user CAD tool that enables the exploratory construction of mechanical papercraft [20]. Other end-user design tools explore different techniques, such as embedding helical springs and joints in 3D prints [6]; adding 3D printed mechanisms to actuate existing objects [13]; maintaining works-like constraints in a system [10]; specifying mechanical behavior [7]; or remixing existing mechanical designs [28]. These end-user systems enable newcomers to explore areas that otherwise would require substantial expertise. For laser cutting in particular, HCI researchers have contributed end-user systems for combining sheet materials with different properties into composite objects [3]; for facilitating cutting onto existing objects [9]; for creating interlocking seams [41]; for designing inflatables [40]; for designing structures that can be assembled with finger-joints [2]; and for modifying existing designs with strain-relief flexures [27]. Most of these approaches do require additional manual assembly steps, for which users need to be informed how different components of the design fit together.

The Lamifold system seeks to extend this related work by contributing a novel set of laminated mechanisms and providing an end-user system that allows users to explore embedding these mechanisms in laser cut objects without expertise in mechanism or lamination design. Lamifold also tries to reduce or even eliminate the amount of assembly required for getting to a functional object. LamiFold allows for fabricating objects by aligning sheets of material, rather than with explicit measurements or coordinate systems. Here we take inspiration from other fabrication workflows that do not require measurement, including StrutModeling [12] and JigFab [11].

## MECHANICAL PRIMITIVES

To support designers in making 3D objects using the laser cutter, we present a set of primitives that offer extensive support for customization. These include limiting the range of movement, locking mechanisms in place, and adjusting the size and shapes of mechanisms. This section presents these mechanical primitives, their workings, as well as their design rationale.

LamiFold offers support for revolute (rotating) and prismatic (sliding) joint primitives. Each LamiFold joint represents a single kinematic pair. We can combine multiple joints in a single LamiFold object, creating a kinematic chain. We can fabricate revolute and prismatic mechanisms which are in plane with the sheet material as well as revolute mechanisms which are orthogonal to the sheet material. We refer to these as planar and out-of-plane mechanisms respectively. This section presents these mechanical primitives, their workings, as well as their design rationale.

### Design Challenges

Although LamiFold mechanical primitives might look simple from the outside, they embed complex mechanisms that are the result of several design and engineering iterations. In earlier iterations, we experimented with laminating living hinges for creating rotational and hinge mechanisms (Figure 8a). However, we noticed that living hinges do not only curve rigid sheet material. They also introduce a significant amount of lateral movement, which is unavoidable and often undesired

(Figure 8b). Additionally, it was unclear how to lock living hinges in place temporarily.

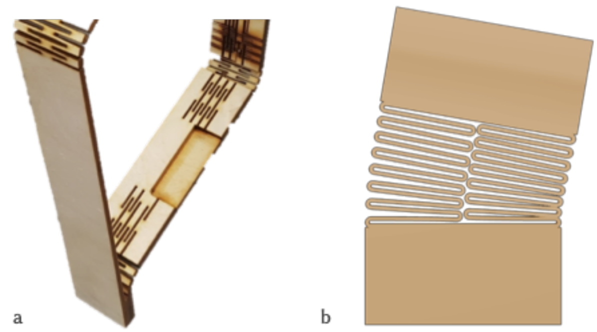


**Figure 8. Early design iterations with living hinges. (a) A laminated linkage made with living hinges. (b) The often undesirable lateral play that living hinges can introduce.**

The core design challenges of LamiFold mechanisms include: (1) Making mechanisms compatible with fabrication with sheet lamination without embedding off-the-shelf components. (2) Support for customization of dimensions and movement ranges. (3) A universal layer design to facilitate combining mechanisms. (4) Creating strong mechanisms. (5) Locking mechanisms to support sufficient loads. (6) Unlocking locking mechanisms. Especially these latter two are particularly challenging when using sheet lamination. In previous approaches, small laminated mechanisms have been locked by soldering copper pads [36]. This approach is permanent, however, and does not support easy unlocking. Additionally, soldering thin pads is not sufficiently robust for large mechanisms.

All mechanical primitives discussed below consist of precisely three layers, making it easy to combine mechanisms into linkages. Our software further facilitates this process as discussed in Section "LamiFold Design Environment".

## Continuous Mechanisms

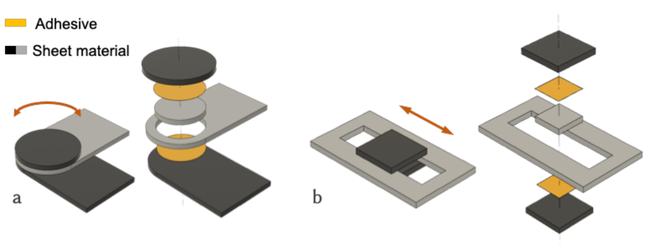


**Figure 9. Mechanisms with continuous motion. (a) Continuous unconstrained revolute joint. (b) Continuous constrained prismatic joint.**

The simplest LamiFold mechanisms offer a continuous movement around a pivot point (revolute) or along a path (prismatic). As shown in Figure 9.a, these mechanisms consist of three laminated layers. While the slot height in a prismatic mechanism defines the range of continuous sliding movement, constraining revolute mechanisms to a specified angle range requires a mechanical stop in the top or bottom layer.

## Detent Mechanisms

LamiFold offers a variety of detent mechanisms. Detent mechanisms constrain motion to discrete steps.

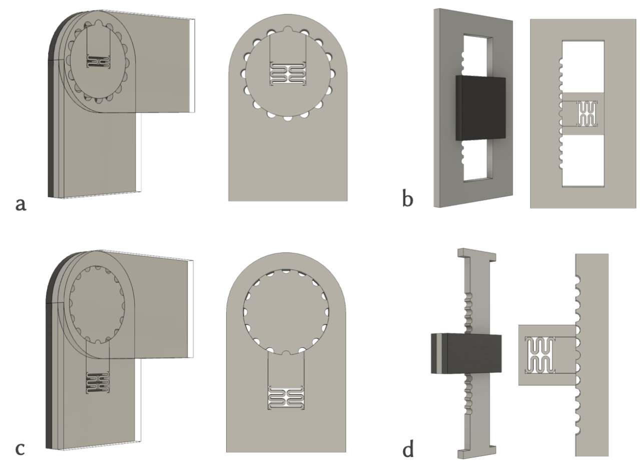


**Figure 10. Basic detent mechanisms. Rotary detent mechanism with (a) inner pawl and (c) outer pawl. Prismatic detent mechanism with (b) inner pawl and (d) outer pawl.**

### *Basic Detent Mechanism*

The most basic detent mechanism for both revolute and prismatic joints is shown in Figure 10.a-b and consists of notches and a spring-loaded pawl. The round notches in the gear or rack ensure that the mechanism can move in both directions.

The compression spring for the pawl can be varied in stiffness by changing the characteristics of its geometry. Varying the stiffness is desirable to change the force required to release the detent mechanism as well as to avoid buckling deformation. The characteristics of the laser-cut zig-zag spring affect its strength and therefore determines the load the mechanism can bear as well as the force required to operate the mechanism. Increasing the width of the spring or alternatively, the thickness of the "spring wires" will make the spring mechanism stiffer. These options are available in the LamiFold software environment.

When LamiFold mechanisms are very small, and no space is available to host the laser cut spring on the inside of the detents, the design can be flipped, moving the notches to the inside and the spring to the outside. Figure 10.c-d shows this alternative detent mechanism for both revolute and prismatic joints.

Similar to continuous revolute mechanisms, detent revolute mechanisms can also constrain their range of movement using a mechanical stop on the inside or outside.

### *One-directional Lock: Ratchet Mechanism*

Ratchet mechanisms are similar to basic detent mechanisms but embed a sawtooth instead of round notches (Figure 11). The laser-cut spring functions as the pawl of the ratchet mechanism. As ratchet mechanisms prevent movement in one direction, they can handle large loads in the reverse direction compared to basic detent mechanisms that are solely held in place by the spring. Adding more coils to the spring mechanism increases the depth of the notches. This, in turn, increases the load the ratchet can handle in the reverse direction before critical buckling cracks the pawl. The height of the notch is equal to the height between the coils multiplied by the number of coils minus one. The LamiFold software environment automatically generates the spring design after entering the height of the notches (Section "LamiFold Design Environment").

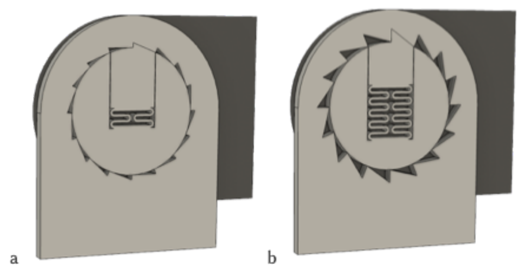


**Figure 11. As the user varies the height of the sawtooth notches, the spring automatically adjusts to increase the number of beams. (a) Short notches and spring. (b) Tall notches and spring.**

Ratchet mechanisms with a limited range of motion, such as prismatic mechanisms and revolute mechanisms that do not rotate 360 degrees, can only pass each position once. This can be desirable for mechanisms that are locked once and remain in place forever, such as a one-time assembly of objects. However, it may be desirable to include ratcheting mechanisms which can be reset. Therefore, LamiFold ratchet mechanisms support embedding a button for releasing the pawl and reversing the mechanism. Figure 12.a-b shows this release mechanism for revolute and prismatic detent mechanisms. Many release handles could be designed, as shown in Figure 12.c. LamiFold uses the designs in Figure 12.a-b as these release handles do not protrude from the surface.

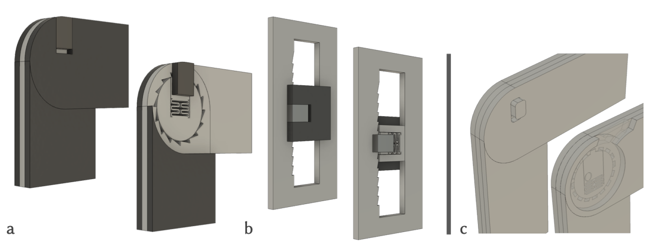


**Figure 12. Ratchet mechanisms with release handles. A coplanar tab release handle for rotary (a) and sliding (b) joints. (c) A protruding release handle.**

### *Two-directional Lock*

To lock mechanisms entirely in place and prevent movement in two directions, LamiFold supports primitives for revolute and prismatic joints, which embed a mechanical latch (Figure 13a-b). These primitives embed U-shaped notches and a handle for locking and unlocking the latch. The spring in these mechanisms ensures that the button is automatically pulled back to the original state when released.

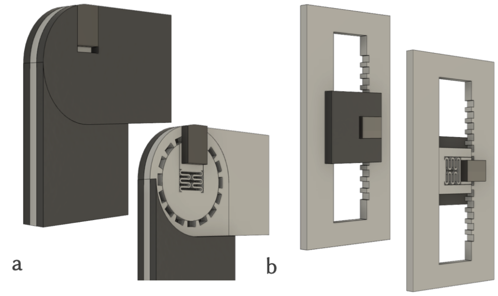


**Figure 13. Revolute (a) and prismatic (b) mechanisms that can lock and unlock using a U-shaped latch.**

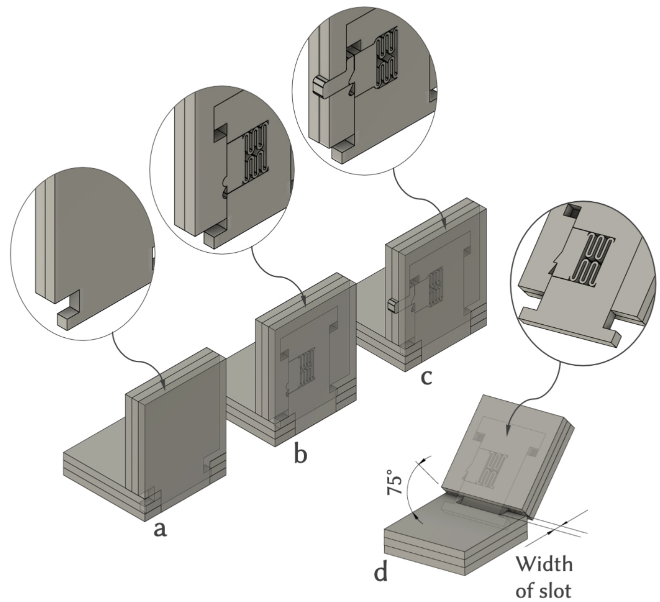


**Figure 14. LamiFold hinge mechanisms (a) Basic non locking hing mechanism, (b) Locking hinge mechanism with sliding mechanism, (c) Locking hinge mechanism with sliding ratchet mechanism and unlocking button (d)Locking hinge mechanism with sliding ratchet mechanism.**

## Hinge Mechanism

To support fabricating functional 3D objects, LamiFold offers an out-of-plane revolute mechanism named hinge. As shown in Figure 14a, we create out-of-plane revolute motion from three laminated sheets of material by laser cutting a square-sized rod in the middle layer and connecting the two parts. Essential for this design is the gap between the two laser cut parts that allows the mechanism to hinge. Any LamiFold 3D object, connected by hinges, thus consist of 3-layer walls to embed the hinge mechanism.

For most applications of hinge mechanisms, it is desirable to lock the hinge in place once rotated to its final state, such as is the case with the desk lamp in Figure 1. LamiFold supports locking of hinge mechanisms by embedding a sliding detent mechanism (Section "One-directional Lock: Ratchet Mechanism") inside one of the hinging parts (Figure 14.b). This internal sliding mechanism has two states, pushing the two hinging parts together, moves the sliding mechanism in the other state. This, in turn, removes the gap between the hinging parts and prevents the mechanism from hinging. When pulling the two hinging parts apart, the slide mechanism switches to the original state allowing the mechanism to hinge.

By embedding a sliding ratchet mechanism as shown in Figure 14.c. ensures a hinge mechanism can withstand larger forces without unlocking. Similar to other ratchet mechanisms, an unlock button is required to move the sliding ratchet back to its original state and allow the mechanism to hinge again.

Hinge mechanisms only lock when rotated to the maximum angle. The hinge mechanism supports angles between 0 and 135 degrees. Reducing the width of the slot in the top layer lowers the angle the mechanism can hinge (Figure 14.d). LamiFold's software environment (Section "LamiFold Design Environment") offers easy control over these parameters.

## LAMINATION WORKFLOW

LamiFold functional objects are optimized for fabrication with sheet lamination using a laser cutter. In our fabrication approach, layers of material are stacked in the laser cutter, where they are cut and selectively glued with the layer underneath one by one. Our approach is compatible with a variety of laser cutters. Depending on the type of sheet materials used, either a CO2 or fiber laser can be used. Sheet lamination is, however, a non-trivial fabrication procedure, especially for larger functional objects with embedded mechanisms. Specific regions in a stack of material have to be cut and removed, while others have to be glued to ensure the final laminated stack can be folded into a functional 3D object. LamiFold's software environment, discussed in Section "LamiFold Design Environment", automatically computes glue stencils and laser cut contours. In this section, we present a streamlined lamination workflow that lowers the barrier for makers and designers to fabricate a laminated object using the software-generated glue stencils and laser cut contours.

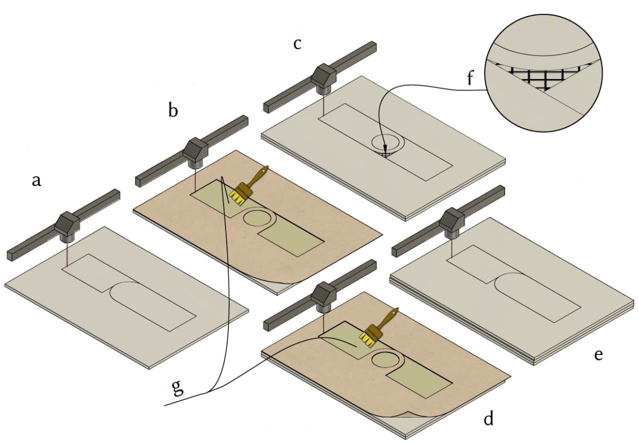


**Figure 15. A schematic overview of our lamination process. (a) the first sheet is cut. (b) a glue template is cut and used to selectively apply glue. (c) the next sheet is cut, excess pieces marked with a hatch pattern (f) are removed. (d) the next glue template is cut and used to selectively apply glue. (e) the final sheet is placed and cut.**

### Leveraging Precision of Laser Cutters

In our streamlined fabrication workflow, sheet materials are laser processed on top of each other and selectively glued inside the laser cutter (Figure 15). This ensures that we leverage the high precision of laser cutters as long as material sheets do not shift position. In contrast, existing lamination workflows [1] process each layer individually and selectively glue regions manually outside the laser cutter. This process is very tedious, as it requires users to align and glue parts manually. Our workflow allows for inserting sheets of material in arbitrary orientations as long as the laser processed region is covered. However, we do recommend aligning all material layers in the corner of the laser cutter as one could accidentally shift layers before the glue in between is cured.

### Removing Parts during the Workflow

Every layer of sheet material requires processing with a laser cutter to create the shape of the object and the functionality of embedded mechanisms. After laser cutting, the LamiFold software environment instructs users to remove excess parts that would be hard or impossible when the next layers are positioned on top. Those parts are marked with an engraved hatch pattern (Figure 15.f). Our fabrication workflow requires sheet material that is at least 4 cm larger than the workpiece at all edges. This border of excess material is only removed at the very end and ensures that the layers on top are always supported and stable, after the removal of parts.

### Selective Deposition of Adhesives

In our initial tests, we experimented with double-sided tape as an adhesive by selectively removing the protective layer. However, we noticed even the strongest adhesive tapes delaminate quickly when moving parts are embedded in the design (Figure 16). Additionally, a significant amount of tape was wasted in regions that do not require adhesive.

**Figure 16. Early lamination experiments used double sided tape which often delaminates.**

In LamiFold's streamlined workflow sheets are selectively adhered using glue. In contrast to tapes, a wide variety of adhesives are available with specific characteristics, such as wood glue, acrylic glue, epoxy glue, and PUR adhesives, for extremely strong bonds between various materials. We mainly used wood glue, as the majority of our example designs are build from MDF. Once the entire material stack is laminated, the curing time for the glues has to be respected before unfolding the object. To selectively apply these liquid adhesives, we use a stencil technique similar to the one used in Silicone Devices [19]. The stencil technique works as follows:

1. Cover the previous layer of sheet material (Figure 15.a) with a large sheet of paper and attach it temporarily using scotch tape. We use recycled brown kraft paper (Figure 15.b).
2. Laser cut the glue stencil, computed by the LamiFold software environment (Section "LamiFold Design Environment"), in the paper and remove all loose parts (Figure 15.b.
3. Apply the adhesive to the cut-out regions in the paper stencil (Figure 15.g). Precision is not crucial as the paper stencil prevents the glue from reaching other regions of the sheet material below.
4. Remove the paper stencil and position the next layer of sheet material on top (Figure 15.c). This layer is now only glued to the layer below in the regions computed by the LamiFold software environment. This process repeats until all layers are glued (Figure 15.d-e).

## LAMIFOLD DESIGN ENVIRONMENT

Designing laminated structures for 3D objects and functional mechanisms is a very challenging and tedious task. The LamiFold software environment significantly facilitates this process by offering convenient techniques to adjust mechanical primitives and export functional objects to laminated structures ready for laser cutting. Our software environment is implemented as a plugin for Autodesk Fusion 360 [8]. As such, all regular modeling features of Fusion are available and can be used in combination with features offered by LamiFold.

### LamiFold Design Process

As we discuss below, designing with LamiFold is an iterative process and involves: (1) inserting and configuring mechanical primitives, (2) adjusting and combining these mechanisms, (3) testing and fine-tuning of the functional object. When the user is satisfied with the functional object, the export feature is triggered.

#### *Inserting and Configuring Mechanical Primitives*

LamiFold offers three main modules: *add rotating mechanism*, *add slide mechanism*, and *add hinge mechanism*. Activating these modules loads a new parametric instance of the respective mechanical primitive and a dialog box for configuring the mechanism. These dialog boxes offer features to configure the mechanical primitive easily. The slide mechanism module, for example, has features to configure, among others, the dimensions, the material thickness, the size of the slot, the spring settings, the style of detents, and the optional release button (Figure 3). Although the material thickness can vary for different layers, LamiFold's export feature expects mechanisms in the same layer to have the same thickness. Changes in the dialog boxes are reflected in real-time in the 3D modeling environment.

#### *Adjusting and Combining Mechanical Primitives*

Once a mechanical primitive is configured, its geometry can be further adjusted and combined with other mechanical or design elements using 3D modeling features available in Fusion. For example, simple *push/pull* and *move* operations, continuously used in 3D modeling, can be used to go from a LamiFold primitive to a mechanism with custom geometry. When making adjustments to core mechanisms, including detents or spring mechanisms, LamiFold cannot guarantee the working.

Combining mechanisms is convenient with LamiFold, as all primitives consist of precisely three layers. After aligning layers of two mechanisms using the *move* operation in Fusion, two overlapping layers can be merged using the *combine* operation. LamiFold does not allow combining multiple adjacent layers as this would change the material thickness and, therefore, the buildup of the lamination stack. When adjacent layers require moving together, those layers can be connected by adding them to one rigid group. LamiFold uses this information to ensure those layers move together while testing the mechanism in software (next step). In addition, information on rigid groups is used to generate glue stencils and ensure the glue is applied to all regions that have to stick together. Besides connecting mechanisms across layers, rigid groups are also used to attach custom-designed elements in Fusion to other elements or to LamiFold mechanisms. As demonstrated in the walkthrough, the custom base plate for the desk lamp was attached to the hinge mechanism by creating a rigid group.

#### *Testing and Fine-Tuning*

At any moment in the design workflow, created mechanisms can be tested in software to allow for further fine-tuning. LamiFold automatically configures "as-built joints" in Fusion for all mechanical primitives. Double-clicking the joint allows for controlling the mechanisms within the valid ranges using direct manipulation controls. Fusion's kinematic constraint solver ensures connected linkages move along.

Besides testing rotation and sliding mechanisms, controlling the joint of a hinge mechanism allows for folding an object to its 3D shape. Especially when embedding multiple hinge mechanisms, testing is essential to ensure all mechanisms unfold and do not block each other.

The joint features allow for testing the movement of mechanisms but do not offer feedback on the strength of a mechanism or the entire object. When feedback on the strength is desired, Fusion's integrated finite element analysis (FEA) provides the possibility to analyze the strength of the LamiFold object. This requires specifying the type of material and the forces that will be applied to the object during use. Any weak spots that the FEA analysis spots can be resolved in the next design iteration. For example, the depth of the notches for detent mechanisms can be increased or the thickness or type of material to reinforce the structure. Ultimately, the strength of objects produced using LamiFold is determined by the materials and geometries that the user specifies.

### Exporting LamiFold Designs

#### *Unfolding and Exporting LamiFold Structures*

When exporting a finalized functional object, LamiFold verifies that all mechanisms and custom design elements in the same layer have the same material thickness. The user is prompted when errors are detected. However, this only occurs for very complex LamiFold designs that combine sheet material with different thicknesses. When the design satisfies this constraint, unfolding the object to a laminated stack

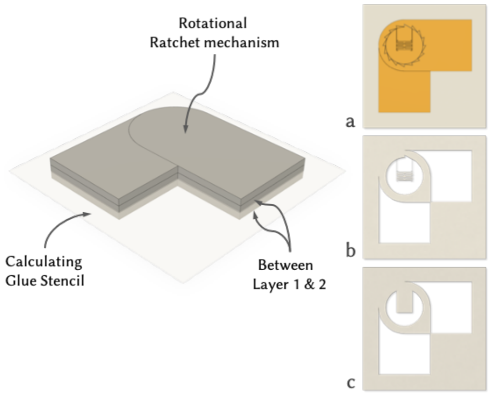


**Figure 17. Generating glue stencils. (a) Extracting contours of coincident faces. (b) Layer interference is calculated. (c) Predefined no-glue areas are added, such as to the pawl.**

is convenient as all moving and folding elements consist of mechanical primitives known to LamiFold. This approach is different from computational approaches that unfold arbitrary 3D meshes to 2D foldable structures [32].

Once a LamiFold object is unfolded to a laminated stack, the contours for laser cutting sheet material are exported to SVG-files, and glue stencils are generated for selectively adhering all pairs of sheet material.

#### *Exporting Contours for Laser Cutting*

While laser cutting a laminated stack, it is essential that enough material is present in the layer below to avoid the new layer to topple before the glue is cured. LamiFold ensures this by maximizing the material in all layers that surround the object inside the laminated stack. Our process, however, also needs to ensure this outer border of excess material can still be removed at the end of the process once all layers are laminated. In LamiFold, this outer border is the convex hull of all object parts in all layers. Using this same outer border in all layers ensures the laminated object is convenient to remove from the laminated stack. In contrast to this outer border, the scrap material between the outer border and the object contour in a specific layer has to be removed before laminating the next layer. LamiFold engraves these parts with a hatch pattern.

Also, some parts inside mechanisms have to be removed after processing a layer of sheet material (Figure 15.c). LamiFold calculates those regions by taking the boolean difference between a layer of sheet material and all parts present in that layer. Those areas are also hatched.

#### *Generating Glue Stencils*

Once a LamiFold object is unfolded, all layers of the material stack can contain elements of different mechanical primitives as well as additional design elements. Elements of mechanical primitives across different layers that move and thus have to be glued together are combined in rigid groups by default. As explained in Section “Adjusting and Combining Mechanical Primitives”, users can define more rigid groups for attaching additional design elements to mechanical primitives or to interconnect mechanical primitives across layers that move together. Generating a glue stencil for selectively gluing elements of two layers is therefore non-trivial.

Figure 17 shows a step by step overview to compute the glue stencil for laminating the bottom two layers of a basic rotational ratchet mechanism. First, the contours of all coincident faces of the two layers of sheet material are extracted (a). We extract those regions by calculating the interference between all faces of the two layers for which the normal point upwards (lamination direction). Next, only contours that are the result of an interference between faces of two rigid groups are preserved as glue regions (b). Finally, the elements that move within a single layer, such as the spring mechanisms, cannot adhere to the layer on top or below. We exclude those regions by adding a predefined “no glue area” back into the glue stencil (c).

## EXAMPLE DESIGNS

Using LamiFold’s software environment, five functional objects, shown in Figure 18, were fabricated: (a) a swing arm desk lamp, (b) a machinist’s toolbox, (c) a chair, (d) a blade saver, (e) a capacitive protractor. Figure 18 also lists the mechanical primitives embedded in these objects. Below we discuss a number of different cases in which the LamiFold design and fabrication procedure can be desired and applicable.

### Functional Mechanical Objects

As discussed extensively in this paper, LamiFold mechanisms can be used to realize functional objects without requiring adjustments to designs to fit existing mechanical parts or requiring extensive assembly. Examples of embedded mechanisms include the swing arm desk lamp and the lid of the machinist toolbox.

### Folding/Unfolding Objects

Folding 3D objects into a laminated 2D stack is not only a feature that can be used during the fabrication workflow, but can also be used at a later time to fold the object flat for storage or transport. For example, our example chair has no moving parts during use, and the embedded mechanisms are only used for folding and unfolding the object.

### Conforming Materials and Surfaces

LamiFold mechanisms can be aggregated, allowing users to create flexible surfaces from many rigid bodies such as chains or chainmail. The blade saver (shown in Figure 18.d) is a simple example object consisting of links joined with revolute joints that can then conform to a disc-shaped saw blade.

### Multi-Material Fabrication

Although the example objects in this paper are mostly built from layers of MDF, our fabrication workflow is compatible with a wide variety of sheet materials such as textiles, acrylic sheets, PET sheets, POM, and conductive sheet material. All compatible sheet materials allowed for processing with a laser cutter (CO2 or fiber laser) in combination with the correct adhesives for bonding can be used for creating multi-material lamination stacks. Allowing, for example, parts that require additional strength to be fabricated from Polyoxymethylene

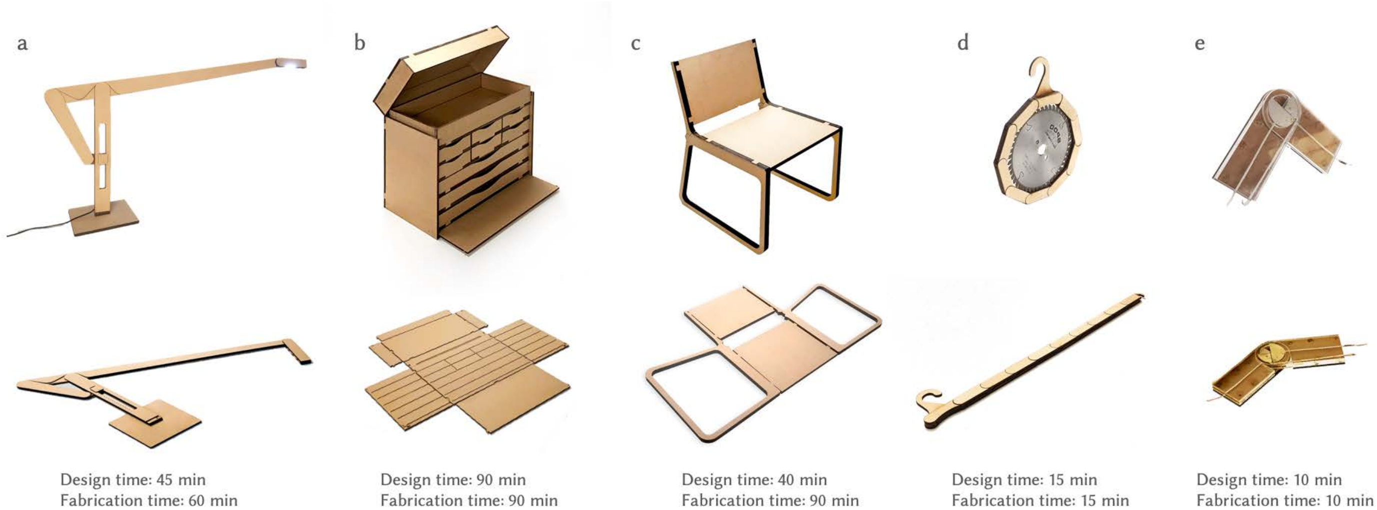


**Figure 18. Photographs of example objects created using the LamiFold workflow. Above: after assembly. Below: as created by the LamiFold process. (a) A swing arm desk lamp. (b) A machinist's toolbox. (c) A chair. (d) A blade saver for circular saw blades.(e) A capacitive protractor**

(POM) material while maintaining low-cost MDF for remaining structures. Alternatively, materials, such as textiles, can be laminated inside or on top of objects to improve aesthetics or comfort. The capacitive protractor Figure 18.e example shows how LamiFold also allows for making functional electronic objects by laminating layers of conductive material, such as copper tape.

## DISCUSSION AND LIMITATIONS

Although LamiFold offers many novel opportunities for prototyping functional objects, our technique also has limitations which reveal many exciting challenges for future research.

First, Lamifold avoids embedding and the assembly of off-the-shelf mechanical parts by laser cutting mechanisms using a lamination workflow. As these mechanisms are challenging to design, LamiFold in many ways trades assembly time for design and fabrication time. To reduce design time, LamiFold offers customizable mechanical primitives requiring the user to design around these elements. Although LamiFold offers many features to customize mechanisms and add custom design elements, objects have to conform to the layered material buildup (e.g., one material thickness per layer). Our example designs show, however, that our approach allows for making a wide variety of advanced functional prototypes. Future research could investigate novel techniques and algorithms to convert 3D models to functional LamiFold objects automatically.

Second, LamiFold supports a variety of features for sliding, rotating, and hinge mechanisms. One obvious extension for the current set of primitives is a locking mechanism for continuous motion. Future versions of LamiFold could also support more kinematic pairs, such as cylindrical, planar, and spherical mechanical primitives. The set of mechanical primitives can easily be extended and new additions will be interoperable with existing mechanisms as long as they are also built from layers.

Third, while our lamination workflow leverages the precision of a laser cutter and therefore does not require manual precision of the user, applying too much glue can cause the glue to spread to undesired regions when applying the next layer of material. We therefore do not recommend using glue that expands while curing. To precisely deposit the correct amount of glue, future versions of Lamifold could leverage novel multi-purpose machines that can deposit substances, such as glue [35]. These machines could also significantly reduce the manual fabrication effort of LamiFold.

Fourth, our lamination procedure can introduce significant material waste. Less material waste can be achieved by optimizing the design to consume as little space as possible in the 2D unfolded version. Additionally, a layer of sheet material does not necessarily has to be a single piece of material, multiple parts of scrap material with the same thickness can be combined in a single layer and laminated into the stack.

Lastly, limitations that are inherent to sheet lamination procedures and fabrication with laser cutters also apply to LamiFold. When cutting the top layer of a stack of material, for example, the layer below is lightly scored, which can result in minor visible artifacts. Porous materials such as wood are prone to warping, which could complicate the gluing process. Unfolding objects to laminated structures could also require processing large sheets of material and thus require a large laser cutter. Future versions of LamiFold could support splitting large laminated structures into multiple parts that are combined outside of the laser cutter work envelope, enabling larger structures to be made.

## CONCLUSION

In this paper, we presented LamiFold, a novel design and fabrication workflow for making functional mechanical objects using a laser cutter. By offering a set of mechanical primitives, our approach allows for laser cutting functional 3D objects without requiring users to embed or assemble third party mechanical parts. Key to our approach is a streamlined lamination workflow which selectively cuts and glues regions of a laminated stack to realize functional and foldable objects. A software design environment supports the user in designing mechanisms and objects for lamination. We demonstrated the utility and versatility of our approach by designing and fabricating a series of example objects with LamiFold.

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