

Foldio: Digital Fabrication of Interactive and Shape-Changing Objects With Foldable Printed Electronics

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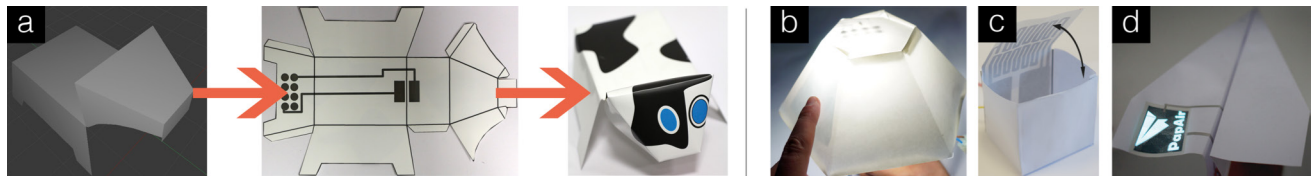


Figure 1. a) Foldios are designed in 3D. Print&fold layouts are automatically generated, including customized printable electronics for sensing and output. The technique enables quick, easy and inexpensive fabrication of a wide variety of folded interactive objects, including b) UbiComp devices, c) actuated shape-changing objects and d) lightweight paper crafts.

ABSTRACT

Foldios are foldable interactive objects with embedded input sensing and output capabilities. Foldios combine the advantages of folding for thin, lightweight and shape-changing objects with the strengths of thin-film printed electronics for embedded sensing and output. To enable designers and end-users to create highly custom interactive foldable objects, we contribute a new design and fabrication approach. It makes it possible to design the foldable object in a standard 3D environment and to easily add interactive high-level controls, eliminating the need to manually design a fold pattern and low-level circuits for printed electronics. Second, we contribute a set of printable user interface controls for touch input and display output on folded objects. Moreover, we contribute controls for sensing and actuation of shape-changeable objects. We demonstrate the versatility of the approach with a variety of interactive objects that have been fabricated with this framework.

Author Keywords

Digital fabrication; rapid prototyping; folding; printed electronics; paper computing; shape-changing interfaces; shape displays; input sensing; thin-film actuator.

ACM CLASSIFICATION KEYWORDS

H.5.2. Information interfaces and presentation

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INTRODUCTION

Custom 3D shaped and shape-changing interfaces are typically fabricated with 3D printing or by manual assembly of different parts and components. While 3D printing enables complex geometries to be printed in a single pass, the interactivity of the objects is very limited. In contrast, manual assembly allows for adding input and output components, such as off-the-shelf touch sensors and displays. However, standard components heavily restrict the possible shapes of interactive objects, as standard components are typically available in only a few sizes, mostly rectangular, planar and rigid. Moreover, mechanical assembly can quickly become complex and time-consuming.

Considering these shortcomings of established fabrication techniques for interactive objects, we introduce **Foldios** (**F**oldable **I**nteractive **O**bjects). A Foldio is an interactive 3D object that is *folded of a thin sheet* of plastics, paper or cardboard. It can *sense user input and provide system output* through *customized printed electronic components* that are embedded within the foldable structure. Foldios are created by designers, makers and even end-users. The approach enables highly customized interactive 3D objects with embedded foldable touch and deformation sensing, display output and actuated shape change (see Figure 1).

Foldios leverage the power of folding. Folding is routinely applied for 3D objects in a variety of domains, ranging from mundane packaging to sophisticated origami or foldable structures in robotics. The high strength-to-weight ratio of folded objects enables thin, very lightweight, hollow and shape-changeable geometries [12]. Foldios also leverage the power of printed electronics, which makes it possible to realize sensors and output components that are very thin, deformable and cover large surfaces. The combination enables a novel and unique way to fabricate an interactive 3D object in a single printing-plus-folding pass (Figure 1a).

The design and fabrication of Foldios involves several challenges. For one, it should be possible to design the interactive object in 3D, rather than requiring the designer to create a non-intuitive and possibly complex 2D crease pattern. Moreover, the approach requires thin-film printable electronic components for embedding sensing and output into the folded structure. Instead of requiring the designer to specify low-level circuit designs for these components, it should be possible to add high-level interactive controls to the 3D model.

The first contribution of this paper is a *design and fabrication technique for foldable interactive 3D objects*, which addresses these challenges. It significantly eases design and fabrication of such objects by a two-fold abstraction: it abstracts both from the 2D crease pattern and from low-level printed electronics. This enables the designer to design the object's geometry in 3D in a standard CAD software. Interactive behavior is added by assigning high-level user interface controls to the 3D model. We contribute a technical enabler for these abstractions: the first algorithmic pipeline which automatically generates from a given 3D model a custom 2D crease pattern with embedded parameterized designs of printable sensors, displays, and actuators. The pattern is then printed using conductive inkjet printing or screen printing and folded to become a 3D object. As a result, highly custom interactive objects can be realized quickly, easily and cheaply.

The second contribution of this paper is a set of *printable controls for on-surface interaction on foldable objects*. They provide an inventory that allows the designer to realize interactive objects with a variety of input and output capabilities, taking into account the specific affordances of folded objects. We present novel controls for capacitive touch input on folded objects and for visual output using thin-film printed displays.

The third contribution is a set of *printable controls for shape-changeable folded objects*. These controls capture shape-changing input and provide shape-changing output using thin-film actuators (shape-memory polymers).

To validate the practical feasibility of the approach, a variety of application examples have been successfully realized with the framework. Areas include interactive paper craft and prototypes, interactive packaging, interactive furnishings, actuated shape displays, and custom-shaped input and output devices. The results demonstrate that a wide range of custom interactive objects can be designed and fabricated easily and in a short time.

BACKGROUND AND RELATED WORK

Fabrication of Interactive 3D Printed Objects

Typical fabrication methods for interactive 3D objects are 3D printing or assembly of multiple components. 3D printing allows for producing objects with complex 3D geometry and fine detail. Prior work has proposed specific 3D printed (passive) geometries that can be made interactive by

adding electronic components after printing. PrintedOptics [2, 34] has shown how the combination of 3D printed passive light guides with external displays or image sensors can enable touch input and visual output on the object's surface. Sauron [26] auto-generates structures inside a 3D object which can be manually augmented with cameras and mirrors to sense user input. An alternative approach generates cavities inside the object, which can be filled with various materials, including liquids and gases, to enable interactivity [27]. While versatile and well-suited for curved geometries, all these approaches require an inner volume in the object. This is problematic for thin and shape changeable geometries.

Alternatively, interactive and shape changeable interfaces can be realized by assembling of electronic components [7, 36]. This task is eased by several off-the-shelf electronic platforms (e.g. Arduino or .net Gadgeteer). However, standard components heavily restrict the set of possible object shapes, and manual assembly can be complicated and time-consuming.

We propose a third fabrication approach: interactivity is added by printing on a foldable 2D sheet. This allows for using existing, fast and inexpensive techniques for 2D printed electronics, enabling a wide variety of components.

Fabrication of Interactive 2D Printed Sheets

Printed electronics enables fabrication of electronic components that are very thin (~10-100 microns) but cover large surface areas. Recent work has demonstrated that components for HCI interfaces can be rapidly and cheaply fabricated in a simple lab environment, using a desktop inkjet printer [10] or screen printing [15]. Printable I/O components comprise capacitive touch and pressure sensors [5, 10, 16, 22], bend sensors [5, 23], active light-emitting displays [15], and thin-film actuators [6].

Previous work has demonstrated UI abstractions for digital fabrication of touch sensors and interconnects [21, 25] as well as for user-customized thin-film displays [15]. Alternatively, the user can physically customize a multi-touch sensor by cutting it to the desired shape [16].

Folded User Interfaces

Folding of thin sheets has been demonstrated to be a powerful approach for fabricating passive 3D objects [14]. Folding has also been investigated extensively as a means for interaction. Previous work has explored interaction techniques for foldable displays [11]. Moreover, folded paper 3D objects have been proposed as tangible input devices. For instance, ModelCraft [30] allows the user to annotate an auto-generated paper model to modify the underlying digital CAD model. Sketch-a-TUI [33] leverages user-folded paper objects as tangible controls on touchscreens. Other work added conventional electronic components to folded objects in order to realize interactive pop-up books [19] or end-user designed interactive paper devices [24]. Lastly, folded paper structures have been actuated with shape-

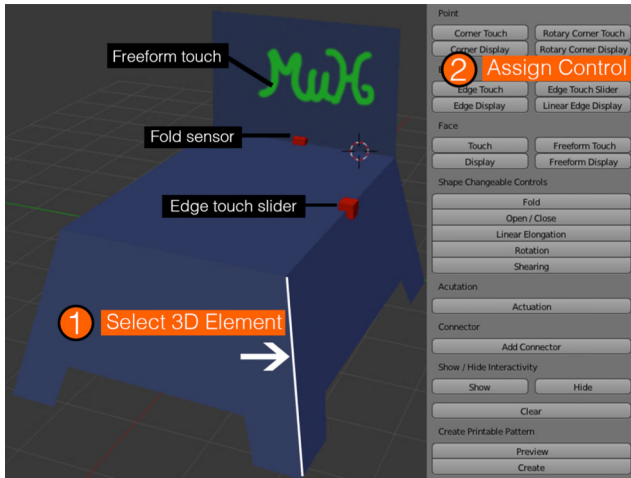


Figure 2. The designer models the object in 3D in Blender and adds interactive controls to the geometry.

memory alloys [18, 20, 36] or electromagnets [17]. All this work has in common that sensing and output is either realized through optical projection mapping or by using conventional electronic components. This limits interactivity and foldable geometries.

THE FOLDIO DESIGN AND FABRICATION PIPELINE

The design and fabrication pipeline of Foldio is illustrated in Figure 1. This section introduces the overall approach and presents a set of contributions, which technically enable the approach and make it usable for designers.

1. Digital 3D modeling of geometry and interactivity

The designer starts by creating a 3D model of the interactive object in a CAD modeling environment. The novelty of our approach is that it allows the designer to model the foldable object in 3D, like any standard 3D object, and to define interactive behavior with high-level user interface controls. Figure 2 illustrates the digital design environment. The user first selects a 3D element (e.g., an edge) that should become interactive. Then, he assigns the interactive behavior (e.g., a touch sensitive slider).

This paper contributes a variety of printable UI controls. We contribute controls in four quadrants of a two-dimensional design space (see Figure 3): controls for *making the outer surface of a 3D object interactive*, through capacitive sensing of touch input and through light-emitting display output; and controls for *shape-change interactivity*, through sensing of folding state and through shape-change output with thin-film actuators. A control can be assigned to a corner, edge or face of the 3D model with a single click (Fig. 2). We have implemented support for UI controls as a Python add-on for Blender, a free and widely used 3D modeling suite. As a result, the designer can use Blender’s powerful built-in functionality for modeling the object.

2. Automatic design of a custom print-and-fold pattern

Next, the pipeline automatically generates a 2D print-and-fold layout for the foldable object (Figure 1a). This raises

technical challenges of unfolding a 3D geometry with embedded printable electronics. We are not aware of any previous automatic approach. We contribute an automated approach to create a parameterized circuit design for printed electronics components, to match given geometric, sensing, and electronic constraints. A further challenge is on the interaction level: how does one provide the designer with real-time feedback on the complexity of the auto-generated fold, while she is modeling the object in 3D?

Unfolding and Parameterized Circuit Design

Unfolding arbitrary 3D shapes is known to be an NP-hard problem. However, for those shapes that can be considered to be practically foldable, the solution space for an unfolded shape is small enough such that heuristics [4, 14, 29, 30, 32] can find a good solution. We used an unfolding algorithm that is based on region growing and implemented in [9]. To work correctly, the algorithm requires a 3D geometry, that has only planar faces. If the 3D model contains curved faces (e.g. a sphere), the designer can use Blender’s built-in functionality to triangulate the mesh.

The result of the unfolding step is a 2D crease pattern with gluing flaps, which however does not yet contain the layout for printable electronics yet. We opted for an electronics-agnostic unfolding step to avoid having the complexity of the unfolded pattern be increased by additional constraints. This ensures the pattern is as easy to fold as possible.

In a subsequent step, our algorithm adds layouts for printable electronics to the 2D crease pattern. Interactive controls which the designer has added to the 3D model are stored as annotations of the 3D model, indicating the type of control and its parameters. The algorithm sequentially processes these annotations and accounts for several parameters: geometric constraints (location, size and shape of the control), the desired resolution of the component, and electronic constraints (min. and max. dimensions and distances between electrodes). If the faces are not large enough for the control to fit in, the user is notified.

The unfolding process may require splitting up the mesh at an edge to flatten it. Each control, that is located on this edge or extends over it, is split into two separate parts. These are reconnected across the fold: the algorithm generates two gluing flaps, one on each side, containing a conductive

	Input	Output
Surface	Corner touch	Corner display
	Edge touch	Edge display
	Face touch	Face display
Shape	Fold sensing	Fold actuator
	Proximity	
	Linear elongation	
	Shearing	
	Rotation	

Figure 3. Design space of interactive controls for Foldios.

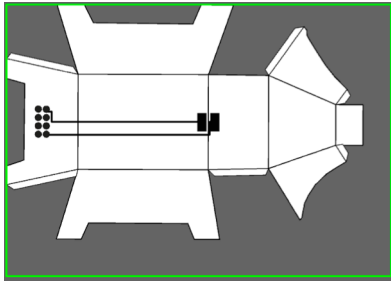


Figure 4. Instant Preview.

pin for each electrode. When the object is folded, a conductive connection between these pins is realized by using double-sided conductive adhesive tape (z-tape by 3M).

Lastly, the algorithm automatically creates conductive traces that connect each electrode with a connector area, where the microcontroller is connected. As folding introduces high mechanical stress at the crease, conductive traces are generated with 2mm width. We use the maze router algorithm [3], which is a powerful algorithm that is used in professional PCB layout tools.

Instant Preview During Digital Design

We have realized a separate application that displays an Instant Preview window (Fig. 4). This window runs the unfolding algorithm and provides a live preview of the unfolded net while the designer is working on the 3D model in Blender. It visualizes the 2D unfolded shape including all layouts for printable electronics, conductive traces and auto-generated flaps. Each element and each group is color-coded. Panning and zooming allows for detailed inspection. Blender and the Instant Preview application communicate via a network socket connection.

The designer can use this information to check the complexity of the crease pattern. Beginners might prefer rather simple crease patterns, while origami experts can cope with highly sophisticated patterns. Independent of skill level, the complexity of the pattern greatly influences the time required for building the object. If desired, the designer can easily reduce the complexity of the crease pattern by using Blender’s automatic mesh simplification function. This trades in geometric level of detail for ease of folding. In addition, the preview window allows the user to judge the quality of the auto-routed conductive traces. If not satisfied with the autorouting, the designer can generate an alternative routing with one click. Lastly, for a quick printability check, the preview window indicates whether the unfolded layout can be printed on a user-defined paper size.

3. Printing

To fabricate the interactive object, the designer prints the automatically generated pattern (Fig. 1). She can choose from two established and affordable printing methods for printed electronics. Conductive inkjet printing [10] is a fully automated and instant method, using an off-the-shelf inkjet printer. It is restricted to printing a single-layer conductor on thin substrates. It supports the touch sensing and

shape sensing controls presented in this paper. The second printing method is screen printing [15]. This is a more time-consuming manual process. It enables printing of light-emitting displays and actuators and supports a wider range of materials, including cardboard and PET sheets up to a size of A3. We recommend to first fold and unfold the substrate once before screen printing on it; this makes conductors more robust to folding. To ensure instant inkjet printouts are robust, we recommend patching conductive traces that go across folds with copper tape. Screen-printed conductors are more robust and need to be patched only if heavily used during continuous shape changing (see Lessons Learned section).

Each Foldio consists of a multi-layer print file with at least two layers. These are printed on top of each other. The first layer defines the folding pattern and is printed using an off-the-shelf graphic printer. The second layer contains all conductive traces, touch controls and the connector. It can be printed with conductive inkjet printing or screen printing. The subsequent layers (dielectric material, phosphor and translucent conductor [15]) are optional and only required for visual output. In addition, we generate a layer containing the outline of the shape for optional laser cutting.

4. Folding

The user manually folds the flat sheet to its 3D shape (Fig. 1). Many crease patterns require parts of the sheet to be cut off before folding. As an alternative to manual cutting, the sheet can be cut automatically with a laser cutter using the auto-generated outline graphic.

5. Using a Foldio

Lastly, a hardware controller is connected to the printed connector area on the folded object. In our current implementation we used an external controlling unit (Arduino or Picoscope as detailed on below), which is connected via wires. Future implementations could use a dedicated FFC connector or embed the controller right onto the Foldio.

During design time, the user can assign a connector area to any face of the model in the same way as the “FaceTouch” control is added. The face must contain a minimum free area of 3.5 x 2 cm. When the print-and-fold pattern is generated, the pipeline also automatically generates high-level method stubs that allow application developers to easily interface with the controls in a high-level language. These allow the developer to easily read out sensor values, control displays, and control actuators in a Processing application. We use the Arduino CapSense Library for capacitive touch sensing. Emit-and-receive sensing was implemented on a Picotech oscilloscope. This functionality could also be implemented as a custom circuit, as demonstrated in [5]. Thin-film displays are realized as presented in [15]. A Processing application serves as the integrating hub: it controls these different HW components and reads out sensor data.

In the following two sections, we will present the Foldio controls for on-surface and for shape-change interactivity.

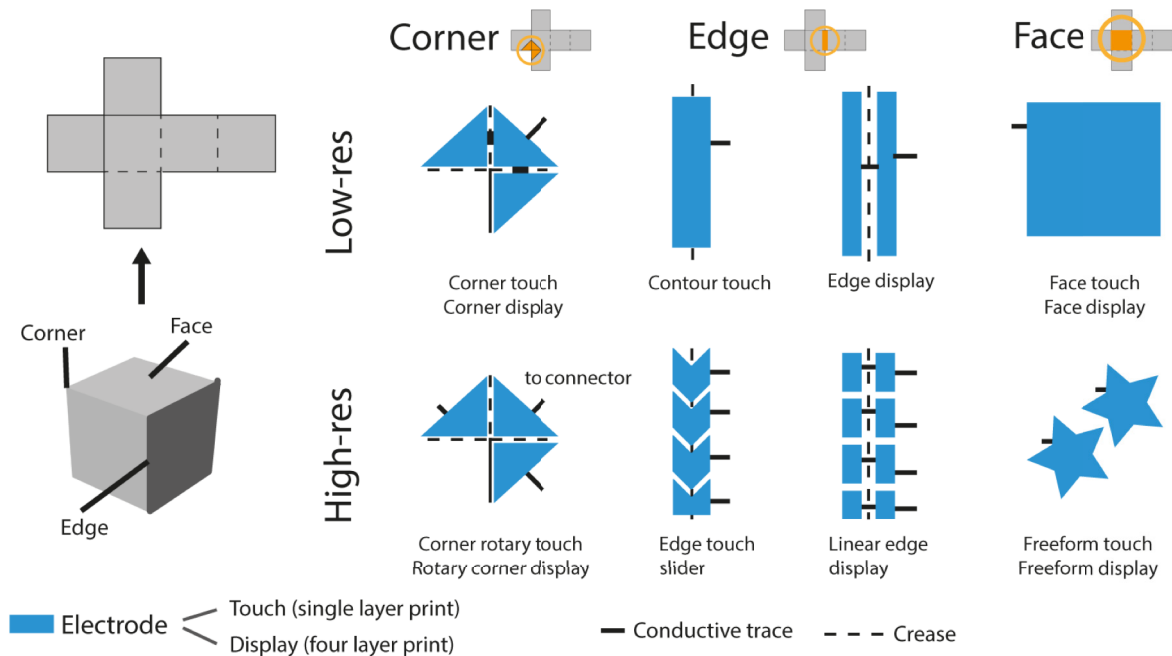


Figure 5. Controls for on-surface touch sensing and visual output.

CONTROLS FOR ON-SURFACE INPUT AND OUTPUT

In this section, we introduce a set of printable UI controls for on-surface interaction with folded objects and present their technical realization. These controls take advantage of the affordances of folded objects. They adapt to their specific 3D geometry and follow subsequent modifications of the model. Each control is defined by a unique combination of folded geometry and printed electronics. A control cuts across all process steps presented in the previous section. First, the designer adds digital controls to the 3D model; a parameterized print-and-fold layout is automatically generated for physical fabrication. The designer implements interactive behavior in Processing by using the automatically generated method stubs of the controls. This approach integrates the control seamlessly with the 3D modeling process and abstracts from its technical realization.

Controls for Touch Input

Foldable objects have unique affordances: Folds provide a natural way to be touched or slidden along. Faces between creases afford to be used as planar interactive surfaces. Corners created by the intersection of two or more folds have the affordance of a button or a rotary knob.

We contribute touch-sensitive controls for foldable objects: any corner, edge or face of the object can be made touch-sensitive by selecting it in the 3D model and assigning a touch sensor control. The resolution of sensing is defined by the designer. In low resolution, the control captures simple touch contact. In higher resolution, the control acts as a circular touch slider (corner), a linear touch slider (edge), or a free-form electrode (face). In addition, a free-form electrode can be defined either by directly drawing on the face using Blender’s texture paint functionality or by placing a graphic onto the face (see Figure 2). Two or more controls of the same type can be grouped. This enables compound controls that span over a larger part of the 3D surface. For example, if multiple edges are selected and defined as a slider, they will behave as one continuous slider.

Controls for on-surface input require only a single layer print and can be fabricated with conductive inkjet printing [5]. Figure 5 depicts the printable base patterns. The base pattern is automatically parameterized to fit the specific geometry and desired resolution.

A *corner control* is realized by automatically generating a triangle-shaped sensing electrode on each neighboring face. For high-resolution sensing, each electrode is separately read out; in contrast, for simple touch contact sensing, all these electrodes are interconnected. Touch sensing on an *edge control* is realized using a single electrode, which extends to both sides across the crease (designer-defined

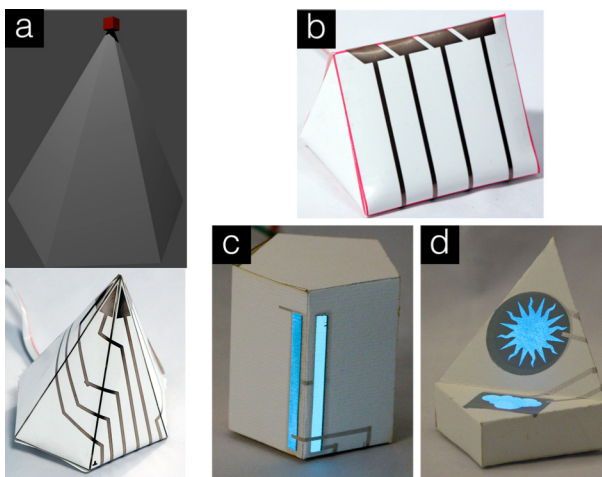


Figure 6. Touch and display controls (folded inside-out for better visibility of electrodes and traces)

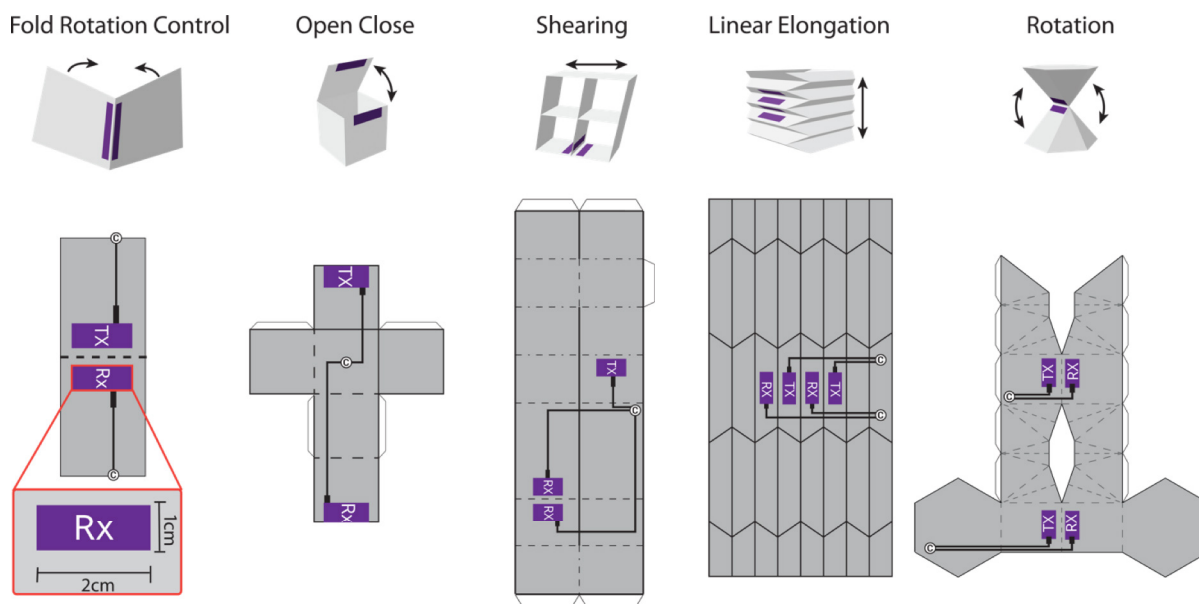


Figure 7. Foldable controls for real-time sensing of shape change

width 0.5–2 cm). For higher resolutions, the base pattern is divided into multiple juxtaposed electrodes, following a widely used pattern for capacitive touch sliders [1]. Lastly, a *free-form* touch sensing element is internally represented as a texture, which is mapped onto the unfolded model and printed as a conductive electrode.

Figures 6a and b depict printed examples of corner and edge sensors. Processing stubs are automatically generated for interfacing with the control in a high-level language. For example, a corner rotary touch control is instantiated by `RotaryCornerTouch t = Foldio.getControl("ctrname")`.

Controls for Display Output

In addition to touch sensing, Foldio offers controls that provide visual output on corners, edges and faces of the folded object. Any *corner, edge or entire face* can be selected to become a light-emitting display segment. Alternatively, the designer can opt for the high-resolution variations of these controls, to display a *circular animation on a corner* or a *linear animation on an edge*. For instance, this allows to communicate a direction or convey progress. *Free-form display segments* can be added onto faces, similar to free-form touch sensors.

Display controls are technically realized through thin-film electroluminescent light-emitting displays. These are printed onto the foldable sheet using screen printing, as introduced in [15]. In contrast to touch sensing, which requires only one layer of conductor, display segments are printed with four layers. As demonstrated in [15], the brightness of each segment can be individually controlled at run-time and display output can be combined with touch sensing. It is also possible to realize segments in different colors, using different inks. To avoid capacitive interference between display elements and nearby controls, we suggest applying time multiplexing between both modes, as done in [15].

Figure 5 depicts the base patterns for these controls. They are the same as for touch sensing, except for the edge display: here, the pattern does not span over the edge. It is divided into two separate parts, which are interconnected by conductive bridges. This makes the displays more robust to strong notches and repeated folding. Figure 6c and d show printed examples of edge and free-form displays.

CONTROLS FOR SHAPE-CHANGING OBJECTS

Folding is very well-suited for realizing shape-changeable geometries [31]. We contribute a set of new embedded thin-film controls that capture the folded geometry in real-time and that provide actuated shape-changing output. The physical instantiation of the controls must fulfill several challenging requirements. First, mechanical components as shown in [8] are hard to integrate, since they increase the thickness of the substrate. Second, the control has to be parameterizable, to be compatible with custom geometries. Lastly, it needs to be easily printable. Ideally it requires only a single layer of conductor, to be inkjet-printable.

Controls for Sensing of Foldable Shape Change

We contribute controls to capture several basic primitives of foldable structures, including simple folding, elongation, shearing and rotations. Each control is a parametrically folded 3D geometry that is shape-changeable and senses its deformation. The overall sensing principle is based on the observation that shape change for folded objects is reflected as a change of the inner angle between two faces in the geometry. To ensure inkjet printability, we base our sensing solution on capacitive emit-and-receive sensing: one electrode emits an AC signal. This signal is received by a nearby electrode [5].

Fold Sensing Control

The most basic type of foldable shape change is the simple fold: the two adjacent faces can be rotated with respect to

each other. The fold sensing control measures the rotary angle between adjacent faces of a fold. The designer can add the control to the 3D model by selecting the edge along which the rotary angle is to be captured.

The base layout of the printed sensor is depicted in Fig. 7. It consists of two electrodes (2 x 1 cm), which are placed on opposite sides of the crease at a 3mm distance. An AC signal (10 Khz, 10 V) is applied on the transmitting electrode (Tx). The strength of the signal on the receiving electrode (Rx) allows the angle to be inferred. To allow the control to measure angles larger than 180°, another electrode pair can optionally be printed on the reverse side. In this case, electrode pairs are horizontally displaced by 2cm to reduce capacitive crosstalk.

Figure 8 shows a plot of the raw readings. The plot shows that even larger angles of up to 180 degrees can be inferred from the raw sensor readings. Yet, using signal strength as a continuous measure is sensitive to influences through capacitive noise. In our experience, the sensor works accurately if the user is not touching any of the electrodes nor interacting with hands or fingers in a 3 cm distance from the electrodes. The influence of capacitive noise can be decreased by printing multiple redundant emit-and-receive pairs at different locations. In addition, the sensor could actively identify if a finger is touching an electrode by time-multiplexing between a touch sensing cycle and an angle sensing cycle. If touch contact is detected, the value from angle sensing is then flagged as compromised.

While the capacitive approach is not ideal for applications that require highly accurate sensing, it provides reasonable accuracy for many practical applications in packaging, paper crafts and prototyping, as we will demonstrate below. These applications leverage on the simple printability of the sensor, its slim form factor and its mechanical robustness.

Proximity: Open/Close Control

Many applications in packaging include lids that can be opened and closed. The open/close control detects proximity between two faces, using the same principle as introduced above. In the 3D modeling environment, the designer selects two edges between which proximity is to be sensed. Open and close states are detected if the signal strength

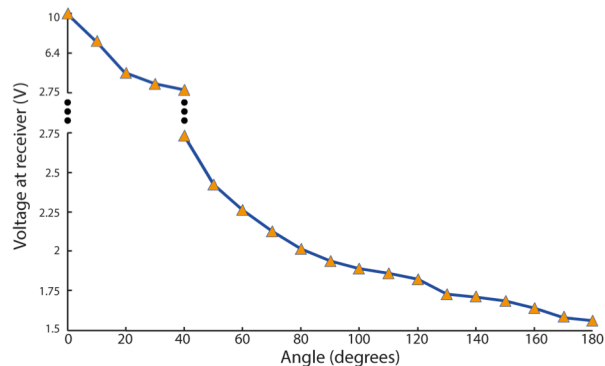


Figure 8. Raw values of the fold sensing control.

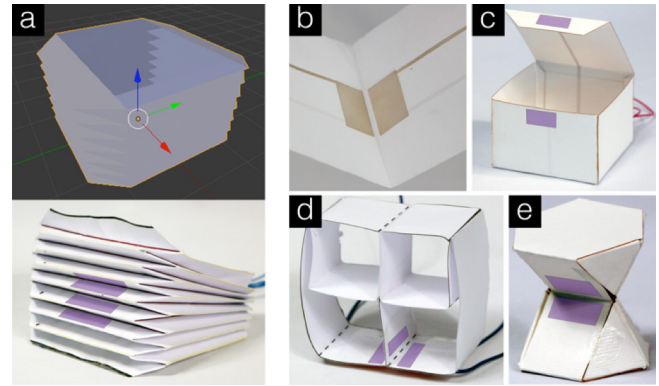


Figure 9. Shape changeable controls (internal sensor placement is highlighted)

rises above or falls below a threshold. Figure 7 depicts the base pattern. Figure 9c shows a physical prototype.

Linear Elongation Control

A variety of crease patterns allow folded structures to be elongated [28]. The bellow fold is one of them. It is very versatile and easy to fold. The pattern was instrumented in previous work with manually placed sensors [35]. We improve on this by offering the user a digital control, that can be customized in size, and in addition we describe a fully printable implementation.

When adding the control to the 3D model, the designer can specify the maximum length of expansion. A customized fold layout is then automatically generated. Once generated, the shape can be scaled further in Blender.

A specific arrangement of capacitive electrodes on the bellow pattern (see Fig. 7) allows the structure to sense its elongation. Each pair of emitting and receiving electrodes is measuring their respective angle, as introduced above. To reduce noise induced by the users's fingers and hands, the pattern contains multiple redundant emit-receive pairs. Figure 9a shows the digital design and a fabricated control.

Shearing Control

Shearing is a basic mechanism in shape-changeable structures [31]. We contribute a shape primitive that can be sheared and senses its state. For instance, the primitive can be used to laterally translate a component which is printed on its top. The structure is based on the crease pattern presented in [31]. Shearing is sensed by three electrodes on the folded structure (see Figure 7). Two receiving electrodes capture the signal, one for each direction. Figure 9d shows a fabricated control.

Rotation Control

The rotation control extends over a simple fold by providing a large movement range and structural stability. The crease pattern is based on [31]. The structure can be continuously moved to the left and to the right and senses its rotary angle. For sensing, the primitive contains two fold sensing controls on opposing sides of the folded geometry. Figure 9e shows a fabricated control.

Thin-Film Actuator Control for Shape-Changing Output

Previous work in HCI has demonstrated applications for shape changing folded objects [18, 20, 35]. Actuation was realized with shape memory alloys, which needed to be knitted into the object, or using pneumatic pumps. Inspired by [6], we contribute a printable thin-film control that actuates a folded structure up to 90°. It makes use of a shape-memory polymer (SMP).

In the digital design environment, the designer selects the edge whose adjacent faces should be actuated. A parameterized printable layout is automatically generated. It consists of two layers (see Fig. 10a). The base layer contains a printed conductive trace, which functions as a resistor to heat the structure on demand (at 6 V, 0.6 A, 2 mm trace width with screen-printed silver ink [15], 40 g origami sheet). A patch of polyethylene tape is attached on top (3M #5421, 0.17 mm thick). Once the resistor heats up to 90° C, the polyethylene patch expands while the base layer retains its length. This results in an actuation of the compound material (see Fig. 10b).

We have conducted a series of experiments to characterize the actuator. The transition from the fully unfolded state to a 30, 60, or 90 degree angle took 33s, 67s, and 122s, respectively. It took around 3 min. to retract to a flat state after heating was switched off. While this is too slow for shape change at interactive rates, it is well-suited for ambient output and for slowly moving structures.

VALIDATION

To validate the Foldio technique, we have realized eight application examples. In this section, we will present the results and discuss lessons learned.

Practical Application Examples

Interactive Paper Craft & Paper Prototyping

Due to its quick fabrication process, Foldio enables the user to quickly explore the combination of shape and interactivity for objects. We demonstrate this with an interactive paper cow (see Fig. 11e). The cow features a fold sensing control. When the head is lifted up, a “moo” sound is played back on an external speaker. Printed electronics are folded to the inside to provide a more visually appealing outer surface. It took approximately 15 minutes to design the 3D model and 25 minutes to fabricate the prototype with conductive inkjet printing.

To demonstrate that Foldios can be very lightweight, we fabricated a paper plane that features a light-emitting dis-

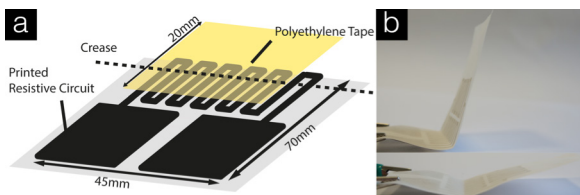


Figure 10. a) Base pattern of the fold actuator control
b) Actuation of a 40g origami sheet (6.5 x 4cm)

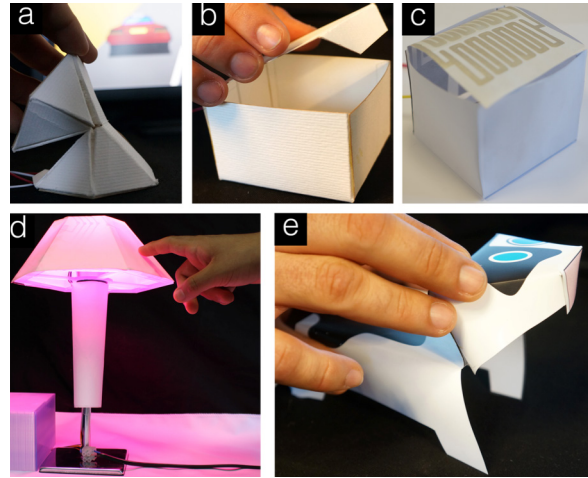


Figure 11. Application cases.

play segment on its wing (Fig. 1d). The device weighs 22 grams including the simple controller electronics and battery. This is lightweight enough for it to fly while lit up.

Interactive Packaging

The high stiffness-to-weight ratio of folded objects enables the fabrication of hollow objects. This makes Foldio well-suited for smart packaging. We have created an interactive box, made of cardboard (Fig. 11b). It senses when its lid is opened or closed using the open/close control. The digital design took 10 min. Fabrication with screen printing took about 2h. Printing the same example using inkjet printing takes only around 20 min. to fabricate.

Interactive Furnishing

To demonstrate use of Foldios for interactive furnishings, we have created an interactive lamp shade (Fig. 1b, 11d). The user can touch the lamp shade to switch a digitally controlled light bulb inside the lamp on and off. Sliding along a crease dims the lamp. We fabricated the lamp shade by screen printing the layout with translucent conductive ink on an A3-sized translucent PET sheet of 0.5 mm thickness. The digital design took about 30 minutes, followed by around 3h for fabrication.

Custom-Shaped Input and Output Devices

Foldio enables quick and easy fabrication of custom-shaped devices that act as specific controllers or provide computer output. As one example, we have realized a game controller that makes use of the rotation control (see Fig. 11a). It offers a direct control of an online car racing game. Design and fabrication on cardboard with screen printing took approximately 2h. Another example is an ambient weather display, which features several display segments for visual output (see Fig. 6d). It took 40 min. to design the object and 3 hours to fabricate it with screen printing.

Shape-Changing Display with Thin-Film Actuation

Lastly, we have realized a shape-changing display (see Fig. 1c in open state, 11c in closed state). Upon incoming messages, the display folds up to notify the user. It is realized

with the fold actuation control. Design of the object took 15 minutes and fabrication with screen printing took 2 hours.

Lessons Learned

By designing and fabricating the application examples, the authors and three additional persons (an interaction designer, a computer graphics expert and a maker experienced in 3D printing) have used the Foldio framework intensely over the course of several weeks. Here we summarize their practical insights and lessons learned.

Fabrication Time

All interactive objects could be designed and fabricated in quickly. Design of an object took a maximum of 40 min; many could even be designed in just 15 min. The physical fabrication of the object took less time with inkjet printing (20-25 min.) than with manual screen printing (2-3 hours).

3D Design

It turned out that the 2D view of the unfolded geometry was an essential tool, that was used during 3D modeling alongside the 3D model view. A typical approach to designing an interactive object was to start by downloading a 3D model from the internet, for instance a lamp shade for the application example, and to add some first interactive controls. Then the unfolded layout was inspected to judge the sizes of the unfolded model and its creases, as well as its complexity. If the crease pattern was found to be too complex, the 3D mesh was reduced with Blender's functionality. This was frequently followed by a phase in which design options for shape and interactivity were more deeply explored in several iterations and cross-checked in the 2D view, before the designer opted for a final layout.

Foldable Geometries

Foldios cannot contain curved surfaces. However, a curved surface can be approximated by subdividing it into folded tessels. We experienced that in practical applications, the unfolding algorithm was not a limiting factor for the set of foldable geometries. For instance, the algorithm was able to unfold a reduced mesh of the Stanford bunny with over 2000 creases in less than a minute. Rather, the set of foldable geometries is limited by the user's skill level in folding and by the time available for folding the object. In our experience, the approach supports very well all those geometries that are mostly comprised of planar surfaces; it is particularly well-suited for lightweight, hollow and shape-changeable structures. Foldios can also be combined with 3D prints (such as inlay, wrap or attached part) to combine the benefits of printed interactivity with curved geometry.

Scalability

The maximum size of the inkjet printer or screen printing frame defines the upper limit of an object's size. We have printed crease patterns on sheets of up to A3 size. Larger objects can be realized by splitting the crease pattern into multiple individual pieces. The maximum number of interactive controls is defined by the number of I/O pins on the microcontroller.

The minimum size of objects is essentially defined by the minimum size of printed electrodes, which need to fit entirely onto a given face. The minimum size of a face with touch sensing or visual output is 5x5 mm. The minimum size for fold or shape sensing is 20x10 mm. The minimum size for actuation is 40x20 mm. The size of the connector area (8 pins) can be further decreased to 1.5 x 1cm by using a standard FFC connector (SFW10S-2STE9LF).

Interface Complexity

Interactive areas and traces share the same space. Too many controls on a small surface can therefore leave too little space for routing the traces. This problem can be addressed by resorting to multi-layer routing, by extending the routing algorithm such that it can route traces over gluing flaps, and by highlighting in the design tool any interactive elements that are too large, such that the designer can reposition or resize them.

Materials

We have successfully printed and folded objects made of thin origami paper (40 g/m²), office paper (80 g/m²), inkjet-printable photo paper (200 g/m²), thin cardboard (250 g/m²), PET sheets (120 g/m²), and thicker cardboard (200 g/m²). Conductors printed on materials of up to 250 g/m² could be folded. In contrast, thick cardboard was problematic because the material broke at the outer creases when folded, damaging the conductor. We recommend printing conductors on such thick cardboard only on the inner side (along valley folds) or to patch them with copper tape. We have also tried to realize objects made of wood (0.5mm foldable microwood paper). We could successfully screen print silver conductors onto the substrate, but the material broke when folded if it was more than 2cm wide. Hence, small objects can very likely be realized with this material.

Repetitive Folding

Repetitive folding for continuous shape change can result in material fatigue at the creases, which can break the traces. We found that inkjet-printed conductors can be slightly folded once for building a 3D object of static shape; however, they do not withstand to very sharp notches (created by sliding with the fingernail across the crease). In contrast screen-printed silver or translucent conductors can be slightly folded and unfolded at least several hundred times. We measured the resistance of a translucent conductor printed on office paper across a fold while we repeatedly folded and unfolded the sample 200 times. We took a data point for every tenth fold. The resistance increased fairly linearly and had increased by 13.5% after 200 folds. With silver ink, a very sharp notch (fingernail) can be folded 5 to 10 times. Generally, conductors across valley folds are more robust to folding than those across mountain folds. In any case, a conductor can be patched with copper tape to be more robust. In addition, the material PET-G is especially resistant to folding and unfolding. Changes in the resistance can require a recalibration of the sensor.

CONCLUSIONS

In this paper, we have contributed a new approach to fabrication of interactive 3D-shaped and shape-changing objects. It is based on a combination of printed electronics and folding. We have demonstrated that a two-fold abstraction enables the designer 1) to design the foldable object in 3D, rather than manually designing non-intuitive 2D crease patterns, and 2) to add high-level interactive controls, rather than manually designing low-level circuitry for printed electronic components. We have presented two sets of printable controls for folded objects, leveraging unique combinations of foldable geometries and printed electronics to enable on-surface input and output as well as shape sensing and actuated shape change. Future work should investigate means for integrating conventional components and for printing components for additional I/O modalities.

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