

Figure 1: FoldTronics creates 3D objects with integrated electronics. Our design software allows users to: (a) Convert a 3D model into a honeycomb structure place electronic components into it. (b) Export the 2D layers (honeycomb pattern, wiring, insulation). (c) Fabricate the layers on a cutting plotter using sheets of plastic, copper regular tape. (d) After soldering and folding, the object is ready to be used: (e,f) This smart watch has a 2D display when collapsed and a 3D volumetric display (3 layers, 6 LEDs each) when expanded – the LEDs and wiring are integrated *inside* the object.

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FoldTronics Demo: Creating 3D Objects with Integrated Electronics Using Foldable Honeycomb Structures

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ABSTRACT

We present *FoldTronics*, a 2D-cutting based fabrication technique to integrate electronics into 3D folded objects. The key idea is to cut and perforate a 2D sheet using a cutting plotter to make it foldable into a 3D honeycomb structure; before folding, users place the electronic components and circuitry onto the sheet.

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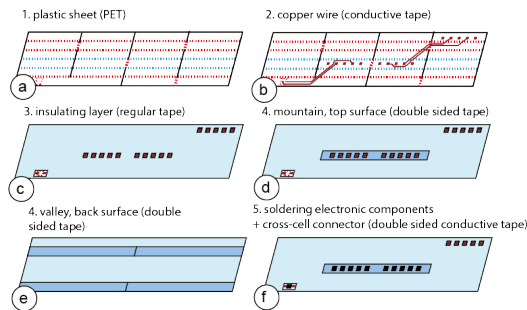


Figure 2: Fabrication process to create a honeycomb structure with integrated electronics.

¹<http://store.voxel8.com/product-catalog/standard-silver-ink-3-cc>

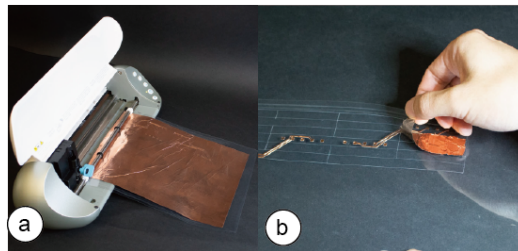


Figure 3: (a) Placing the copper sheet. (b) After cutting, we can peel off the rest.

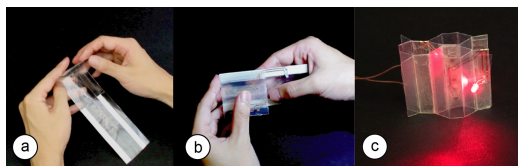


Figure 4: (a, b) Folding the honeycomb. (c) Assembled functional LED circuit.

The fabrication process only takes a few minutes allowing to rapidly prototype functional interactive devices. The resulting objects are lightweight and rigid, thus allowing for weight-sensitive and force-sensitive applications. Due to the nature of honeycombs, the created objects can be folded flat along one axis and thus can be efficiently transported in this compact form factor.

KEYWORDS

personal fabrication; 2D folding; electronics

INTRODUCTION

While many of today's fabrication processes allow users to fabricate passive 3D objects, fabricating 3D objects with integrated electronics that allow for interactive applications remains challenging [1]. For instance, while it is now possible to 3D print the wires of a circuit using silver ink (e.g., *Voxel8*¹), there is only little progress in fabricating the actual electronic components themselves. *ActMold* [4] places electronic circuitry onto a plastic sheet prior to draw-forming a 3D structure from it, and *Foldio* [2] prints circuitry onto a 2D sheet that the user can cut and fold. However, those methods only apply electronics to the surface of an object.

In this paper, we take a different approach: Inspired by existing methods that fold passive 2D sheets into honeycomb structures [3] to create rigid and lightweight objects, we propose a new fabrication technique that combines honeycomb structures with integrated electronics (Figure 1). Our method goes beyond existing origami-electronics applications by providing a fabrication pipeline supported by a design tool that facilitates the creation of interactive objects. Users only have to use a regular cutting plotter to cut the 2D sheets into a specific pattern, add the electronic components, and then fold the structure into its final 3D shape.

FABRICATION PROCESS

Figure 2 summarizes the layer-based fabrication process at the example of making a simple LED circuit with one cross-cell circuit connector and a battery connection. The fabrication took 2 minutes for cutting the plastic sheet, 3 minutes for cutting the copper foil, 1 minute for cutting the insulating sheet, 2 minutes total to cut the double-sided tape on each side, and 10 minutes to assemble.

Cutting / Perforating the Sheet: We start by cutting and perforating the base sheet to create the mountain, valley, and slit lines.

Placing the Wiring with Copper Tape: Next, we place a layer of one-sided copper tape across the entire sheet (Figure 3a). We put the sheet back into the cutting plotter with the copper side up and cut out the shape of the wires. We then peel off the copper tape that is not part of the wiring (Figure 3b).

Insulating Sheet: In order to prevent any short circuiting from wires touching after folding the base sheet, we next add an insulating layer.

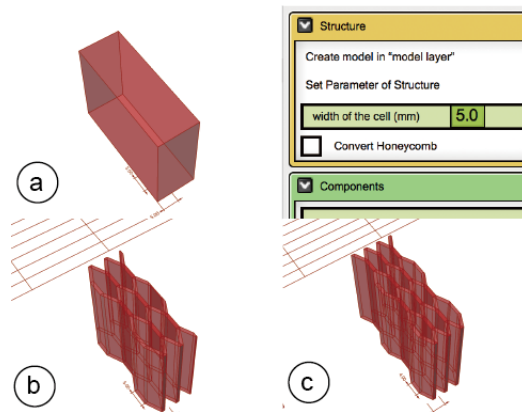


Figure 5: (a) Convert the model into (b, c) honeycombs with different resolutions.

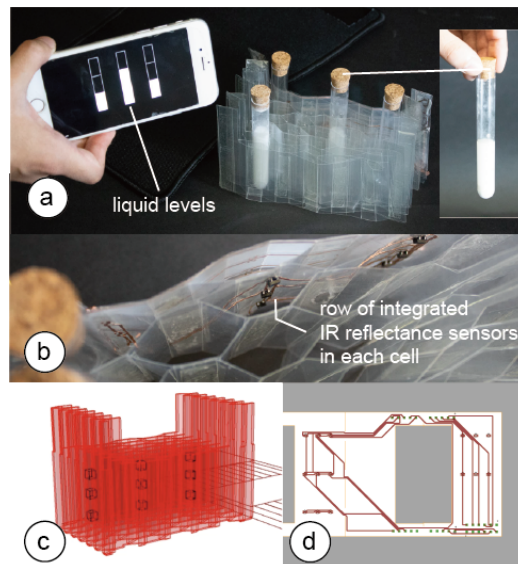


Figure 6: (a, b) Tube case with sensors. (c) 3D model data, (d) circuit layout.

Glue mountains/valleys to hold after folding: We apply a layer of regular double-sided tape to the sheet on both its bottom and its top. The double-sided tape is used to connect the valleys and mountains that hold the honeycomb structure together after folding.

Soldering & Folding: We cut off the honeycomb pattern to disconnect it from the sheet. Next, we solder the electronic components onto the wires using a soldering iron and finally fold the the honeycomb together (Figure 4).

USER INTERFACE FOR CONVERSION SOFTWARE

To allow users to easily design honeycomb structures with integrated electronics, we created a user interface in the 3D editor Rhino3D that facilitates the design process as a Grasshopper extension.

#1 Convert 3D Model into Honeycomb Structure: Users start by creating a 3D model in the 3D editor (Figure 5a). After finishing their design, users can convert their 3D model into a honeycomb structure by pressing the "convert" button. After our algorithm split the model into honeycomb cells, the result is displayed to the user in the 3D view (Figure 5b).

#2 Placing Sensors, Actuators, Display Components: To add electronic components into the layout, users select the type of component (LED, photo sensor, cross-circuit connector etc.) from the menu and add it by clicking the respective button. This automatically creates a 3D model of a box representing the size of the selected electronic component. The user can now drag the electronic component to a location in the 3D volume.

#3 Exporting the 3D structure: Once users are done with placing electronic components, they can hit the "export" button. On export, our 3D editor plugin creates all layers of the fabrication stack as 2D drawing files (.DXF file format) except the wiring layer, which will be created separately in a later step in the process.

SCENARIOS

We illustrate several scenarios that benefit from having integrated electronics in foldable 3D honeycomb structures.

#1 Tube Case with Liquid Levels (Integrated Sensing)

Figure 6 shows a portable test-tube case that can detect if tubes are inserted or removed, the type of liquid they contain, and the current liquid level. After measuring, the portable test-tube case displays the tube's content quantity and color in real time on the user's phone.

To allow for sensing inside the 3D structure, we placed three IR reflectance sensors per cell onto the 2D base sheet prior to folding the structure into its three-dimensional shape. Once folded, the sensors can detect a test tube inserted into one of the honeycomb cells.

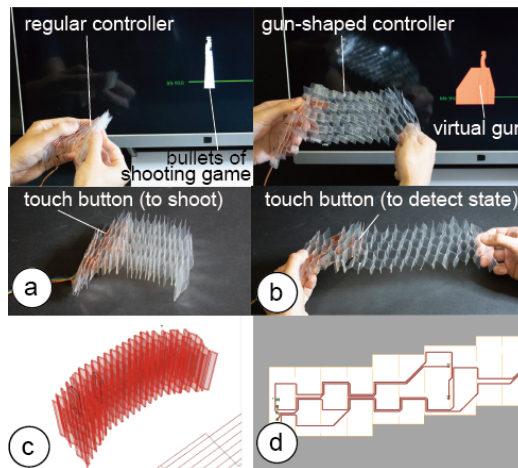


Figure 7: Shape changing controller. (c) 3D model data, (d) circuit layout.

#2 2D + 3D Smartwatch Display (Integrated Displays)

Figure 1 shows a prototype of a smart watch: (e) By default, the smart watch provides a regular 2D display (for simplicity of prototyping we use a display made from 2x3 LEDs). (f) However, when the user pulls the watch face upwards, the 2D display transforms into a volumetric 3D display for viewing additional content. To detect when the display state changes from 2D to 3D and the additional LEDs need to be turned on, we also integrated a sensor that can detect when the display is in its flat 2D state. The key idea is to place conductive wires in a way that they touch when the display is compressed, and do not touch as the display gets expanded. We support this "touch sensor" in our design software as a separate electronic element.

#3 Dynamic Game-Controller (Integrated Sensing)

Building onto the functionality explained above, we also build a game-controller that users can transform into different shapes to represent different game states, e.g., from a regular controller to a gun-shaped controller as shown in Figure 7. The controller includes two of the touch-buttons explained in the previous example: one touch button operates the controller and allows the user to shoot objects, whereas the other touch button detects the state of the game controller.

CONCLUSION

In this paper, we presented a novel fabrication technique that allows users to integrate electronic parts into foldable 3D structures. Since our technique is based on using a plotting cutter and a plastic sheet, users can create prototypes fast and at low cost. To facilitate the design, we developed a layer-based fabrication method and developed software that automatically generates the required layers for folding, circuitry, and insulating. We demonstrated how our technique can create a variety of 3D objects with integrated functions.

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