PEP (3D Printed Electronic Papercrafts): An Integrated Approach for 3D Sculpting Paper-Based Electronic Devices

Hyunjoo Oh[1], Tung D. Ta[2], Ryo Suzuki[1], Mark D. Gross[1], Yoshihiro Kawahara[2], Lining Yao[3]
[1]University of Colorado Boulder, [2]University of Tokyo, [3]Carnegie Mellon University
{hyunjoo.oh, ryo.suzuki, mdgross}@colorado.edu, {tung, kawahara}@akg.t.u-tokyo.ac.jp,
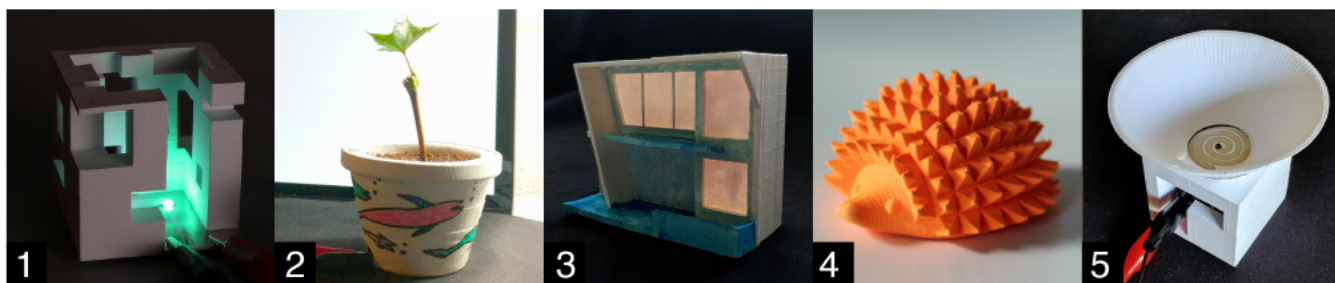liningy@andrew.cmu.edu

Figure 1. Examples of Printed Electronic Papercrafts: (1) sculptural cube lamp; (2) moisture sensing flowerpot (3) architectural model with simulated lighting; (4) smart toy armadillo with RFID tag; (5) loudspeaker.

ABSTRACT

We present PEP (Printed Electronic Papercrafts), a set of design and fabrication techniques to integrate electronic based interactivities into printed papercrafts via 3D sculpting. We explore the design space of PEP, integrating four functions into 3D paper products: actuation, sensing, display, and communication, leveraging the expressive and technical opportunities enabled by paper-like functional layers with a stack of paper. We outline a seven-step workflow, introduce a design tool we developed as an add-on to an existing CAD environment, and demonstrate example applications that combine the electronic enabled functionality, the capability of 3D sculpting, and the unique creative affordances by the materiality of paper.

Author Keywords

3D sculpting; papercraft; paper electronics; fabrication techniques; prototyping

ACM Classification Keywords

H.5.m. Information interfaces and presentation: Misc

INTRODUCTION

Paper is a good medium for prototyping in many fields, including artistic and craft practice, scale models in

architectural design, low-cost rapid prototyping for manufacturing, to name a few. Compared with the plastics used in stereolithography and fused deposition modeling, paper is inexpensive, lightweight, ubiquitous, and environmentally friendly, and easily affords creative expression. Unlike plastic we can fold, bend, or cut paper; and draw, paint, or print on it. And as electronic components become smaller, thinner, and lighter they can be attached and embedded in products made of paper. We can draw or print circuits on paper and in place of soldering, we can glue or tape electronic components.

While traditional papercrafts commonly cut, bend, and fold paper in its natural sheet form, cutting and laminating many sheets together creates solid objects similar to what 3D printing methods produce. As this selective deposition laminating (SDL) method involves removing material from each sheet before gluing cut sheets together, we refer to the process as '3D sculpting'. In the PEP project we integrate electronics into sculpted papercraft and ask: What unique expressive and technical possibilities might this combination enable?

Sculpting electronic papercrafts is a powerful technique that opens a new creative space in rapid prototyping of interactive products. Figure 1 shows several examples made using PEP techniques: Printed conductive layers embedded into 3D sculpted papercrafts, for instance, can light a lamp (Figure 1-1), sense moisture (Figure 1-2), or amplify sound (Figure 1-5). Electroluminescent layers (Figure 1-3) and RFID tags (Figure 1-4) can be fastened to paper and embedded into the product. We stack paper and insert functional layers with printed conductive traces, cut the

paper to form 3D objects, extend circuits by bending sheets or carving vertical channels on the conductive printed parts and decorate the resulting objects with craft supplies.

The PEP (Printing Electronic Papercrafts) project comprises a software editor and a set of fabrication techniques. The editor enables a designer to select a 3D model from a database, embed functional layers of electronics into the model, and modify its structure to connect functional layers into a single circuit. Our fabrication techniques support design and engineering to embed actuation, sensing, display, and communication into sculpted 3D products.

In the pages that follow we first summarize the advantages of these techniques. Then we review related work and describe the workflow to create Printed Electronic Papercrafts and outline the fabrication techniques and their capabilities. Next, we introduce the design platform where we plan and produce digital files. We demonstrate some applications and describe how we employed the PEP editor and fabrication techniques. Finally we conclude by discussing the limitations of PEP and outline future work.
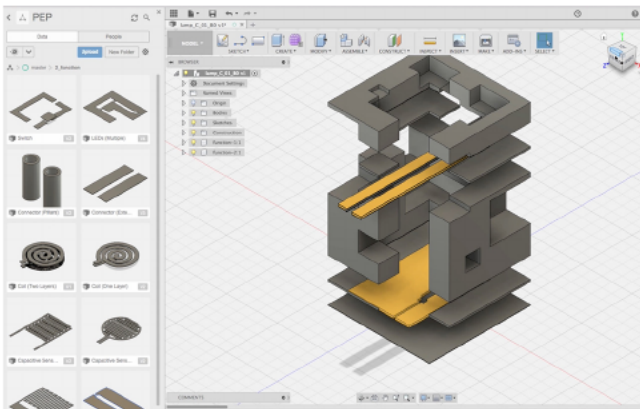
Figure 2. PEP software editor to integrate functional layers into a 3D model

CONTRIBUTIONS AND BENEFITS

The main contributions of this work are:

- Design techniques and process to creating 3D electronic devices from a stack of paper;
- A design platform add-on to an existing CAD environment, with a database of tested and parametric electrical and geometric components;
- Primitives that demonstrate the integration of four functions into 3D paper objects: actuation, sensing, display, and communication;
- Examples that show how PEP software and fabrication techniques generate new expressive possibilities.

Advantages of 3D Sculpting Paper

Our paper manufacturing techniques have several advantages over existing multi-material 3D printing processes that can print electronic products such as thermoplastic based Voxel8 [39] and photocurable resin based ChemCubed [6].

1. Paper is widely available, accessible and affordable and we integrate it with thin film electronic components.

The main material we use in PEP is common office copy paper, which is ubiquitous and recyclable. Likewise, thin film electronic components, which we combine with plain paper, are widely available, accessible and affordable.

Benefitting from the recent development of thin film- and paper-based electronic printing technology, PEP enables designers to deploy a larger variety of functional components, from simple resistive heating coil (Figure 20) to RFID tags (Figure 17).

2. 3D electronic papercrafts are robust.

Embedding electronic parts in a PEP object produces more durable products than other approaches. For instance, Voxel8 [39] is a commercial 3D electronic printer that integrates fused deposition modeling (FDM) and conductive paste extrusion. According to the Voxel8 design guidelines, the silver shrinkage buffer is 40%. Therefore, the connections of the circuit inside a Voxel8 printed object tend to break due to differential thermal shrinkage between the non-conductive thermoplastic and the conductive silver paste. We use silver nanoparticle ink to print conductive traces on functional layers, which minimizes thermal movement.

3. 3D papercraft leverages the unique material properties and aesthetics of paper.

An engaging medium enables continuous experimentation, which yields a variety of outcomes [20]. Paper's unique materiality, which encourages diverse expressive exploration, explains why traditionally many creators prototype with paper. By augmenting paper prototypes with functional behaviors PEP can be a compelling medium for interaction designers. For instance, Figure 14 shows an architectural model 3D sculpted with embedded electroluminescent layers and painted in watercolor. Novices with little or no experience in 3D design or electronics can also employ it as a quick way to embed rich features into 3D printed objects.

RELATED WORK

2D and 3D Printing of Electronics

Traditionally, prototyping of electronic circuits has been done by subtractive techniques such as etching or milling. Recently, however, the development of printable conductive material has enabled an alternative prototyping approach that leverages additive manufacturing processes. One popular approach is 2D inkjet printed circuits [12, 13, 18]. Recent work also highlights the combination of automated pick-and-place and elastomeric conductor extrusion for sheet-like electronic material [37].

The emergence of multi-material 3D printing suggests integrating electronic circuit into 3D printed objects. Voxel8 [39] implements this by printing conductive paste at

the same time as thermoplastic materials. However, the resolution of electronic circuit printing is low, and the difference in thermal expansion of conductive paste and thermoplastic results in broken connections inside the 3D printed structure. The ChemCubed process [6] uses inkjet printing to deposit silver nanoparticle ink along with a UV-cured polymer. However, the printed object requires sintering to make the electronic pattern conductive, and the machine is expensive.

Integrating Interaction into 2D and 3D Printing

Several efforts integrate interaction in 3D printing for rapid prototyping of interactive physical objects. For example, Pineal [19] allows a user to integrate a smart watch or phone into 3D models. The user can specify high-level behaviors of the interactive 3D printed objects through a specialized design tool and programming environment. Similarly, .NET Gadgeteer [38] also provides a means for rapid prototyping of the interactive behavior embedded into the 3D printed objects. However, integrating interaction with a microcontroller or a smart watch or phone can be costly and require adopting a particular toolkit. In contrast, our approach using embedded electric circuits is more inexpensive and affordable. As circuit design may require users to make lower level decisions, we provide a database of designs and a novice design tool to support the design process.

Similar to our approach, SurfCuit [35] integrates circuits into 3D printed objects. Whereas SurfCuit installs a circuit on top of a surface of a printed object, PEP embeds the circuit into 3D printed papercrafts. Recently, several works have explored the embedded approach to integrate interaction. This includes 3D printed objects that can sense deformation [5, 31] or touch [32] using carbon doped thermoplastic. Taking an inspiration from these works, we expand the design space of embedded interaction not only in sensing, but also in actuation, display, and communication.

Multi-layered material fabrication with different material properties in the composite is prepared by conductive inkjet printing or screen printing. These material composites are used for actuation [14], display [24], and sensing [25]. Or, using both additive and subtractive methods via a laser cutter, rigid, bendable, and flexible properties are embedded into the composite [27]. Whereas previous work developed "smart" sheets and used them to create 3D shapes by bending and folding, instead we sculpt a volume of a stack of paper. Our application examples demonstrate that our different approach enables a unique design space.

To employ soft and flexible materials for 3D printing, researchers have experimented with needle felted yarn [17], fabric [26], and textiles [29]. Whereas previous work used only additive manufacturing, our effort, which combines additive and subtractive methods adds another material, paper, into the list of nontraditional, soft, and flexible materials for 3D printing.

Electronic Papercrafts

Researchers have demonstrated design and fabrication techniques to integrate electronic and computing components with various forms of papercrafts such as a pop-up book [28], an invitation card and a headphone [33], a robot, a speaker, and a lamp [30]. To empower the creation of electronic papercrafts, conductive connection methods employing craft supplies, such as conductive tape, pen [8, 10], paint [5] and stickers [7, 16] have been developed and some have become inexpensive off-the-shelf products.

PEP explores the combination of electronics and papercrafts to enable a new creative space, and focuses on such integration by digital fabrication, in particular 3D sculpting, whereas previous work investigated embedding electronics into paper mostly by handcrafting techniques.

OVERVIEW: PRINTED ELECTRONIC PAPERCRAFTS

PEP is a body of techniques to integrate interaction into printed papercrafts via 3D sculpting. We explore the design space of PEP in four functional aspects: actuation, sensing, display, and communication. When we insert these functional layers into a stack of plain paper, we can form 3D products that also embed interactive functionality. Each sheet of paper is thin, flat, and flexible; we stack many sheets to create volumetric solids while retaining the affordances of paper. Hence, integrating a stack of plain paper with paper-like functional layers can provide new expressive and technical opportunities for human-computer interfaces and applications (See Figure 3).
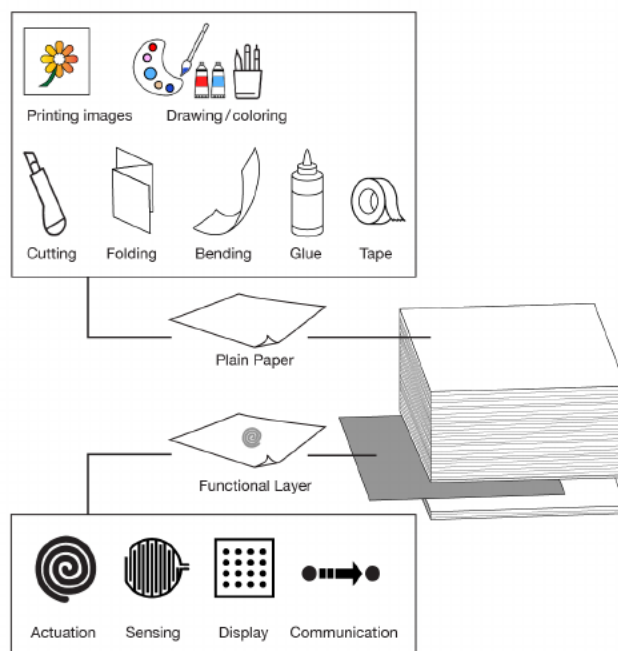
Figure 3. Composite structure of paper and functional layers. Paper supports cutting, folding, and bending to construct 3D forms; craft techniques add images and colors. Functional layers embed actuation, sensing, display, and communication.

In order to sculpt a product from a stack of paper, we use Mcor's IRIS printer [21]. This printer applies glue to the layer on the build platform, advances a sheet from the paper tray and attaches it to the stack on the build platform, cuts a slice of the 3D form in the top sheet, and repeats this process. It produces a volumetric object using the stack of paper and embeds functional layers within the object.

PEP FABRICATION WORKFLOW AND TECHNIQUES

Workflow

Figure 5 shows how we use the PEP techniques to create a printed electronic papercraft. We design with the PEP editor, develop functional layers, compose a stack of paper with the functional layers, print 3D products, connect the functional layers, and decorate the product using craft supplies.

Step 1: Design the 3D Form in the PEP Editor

We use the PEP editor add-on in Autodesk's Fusion 360 [3], a widely-used existing CAD application. We can design a new 3D model or import one from our library. Then, selecting a surface in the model brings us to the next step: choosing a functional component to apply, and adjusting parameters or positions of the imported components. Once the design process is completed, we can download the functional layers as PDF files and the 3D model as an STL or OBJ file.

Step 2: Prepare Functional Layers

The functional layer can be prepared with different processes such as inkjet printing, silkscreen printing or simply attaching thin-film electronic components to paper.

Inkjet printing: We print conductive patterns with silver nanoparticle ink using a commodity inkjet printer. The printed silver ink can serve as wiring traces for LEDs, capacitive or resistive sensing, and coils for RFID tags or sound production. Passive components such as resistors, capacitors, and inductors can be designed and printed directly with silver nanoparticle ink.

Silkscreen printing: Some materials cannot be inkjet printed; these we prepare by hand. We used silkscreen printing to make cuttable electroluminescent sheets for lighting applications.

Attaching: Many electronic components are becoming smaller, thinner, lighter and commercially available. We can attach them to a paper sheet with glue, paint, or tape. The printer grabs, stacks and glues the sheet along with its electronic component: an RFID tag, bend sensor, or any thin-film electronic component.

Step 3: Prepare Printing Materials

Now we prepare the input stack of paper, inserting the functional layers at positions indicated by the PEP editor. The Mcor IRIS printer calculates the number of sheets, counting 0.1mm per sheet;100 sheets will produce a 10mm height object.

Step 4: Sculpt a 3D Model

Now we load the 3D modeling file into the Mcor application and set the position and orientation of the imported model for sculpting. Essential here is to place the 3D model with functional layers horizontal. The build size is 9.39 x 6.89 x 5.9 inches (using US letter size) or 256 x 169 x 150mm (using A4 size paper).

Step 5: Post-Process the Print

When the Mcor printer is finished, we unload the platform and extract the sculpted product. We use tweezers to remove small bits of waste material (See Figure 4).

As the product comprises many attached layers of thin sheets, it is easier to remove parts in the horizontal direction than vertical. Removal is also more likely to damage horizontally attached parts than vertically attached ones (See Figure 21). Damaged parts can be repaired using a knife, glue and tape. At this stage, we also fix any connections in the functional layers that were damaged while printing.

Step 6: Connect Functional Layers

We can connect multiple conductive layers into one circuit by either (1) extending a printed circuit layer and bending it to connect with another layer, or (2) filling vertical channels with conductive adhesive (Figure 6). We can choose either method in the PEP editor, and the editor adjusts the model. For bending, the thickness of the extended parts is 0.2mm, which employs two sheets of paper in order to support smooth bending. For carving the channels, we made the outer diameter 5mm and the internal hole diameter 3mm.

Step 7: Augment with Craft Supplies

The unique materiality of paper products enables various expressive explorations. We can decorate and color using craft supplies such as pens, watercolor, and acrylic paint. Especially as the PEP techniques add electronics into papercrafts, it opens another expressive exploratory space. For instance, we can integrate heat-generation in the printed object and add changing colors using thermochromic pigment (Figure 20).
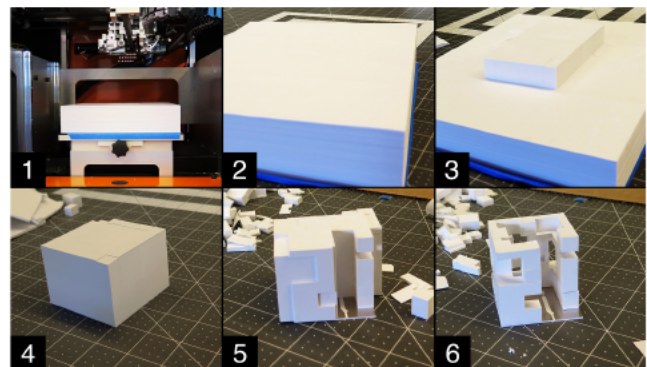

Figure 4. Extracting the rest of the printed object by using a tweezers and fixing damaged parts with craft supplies.
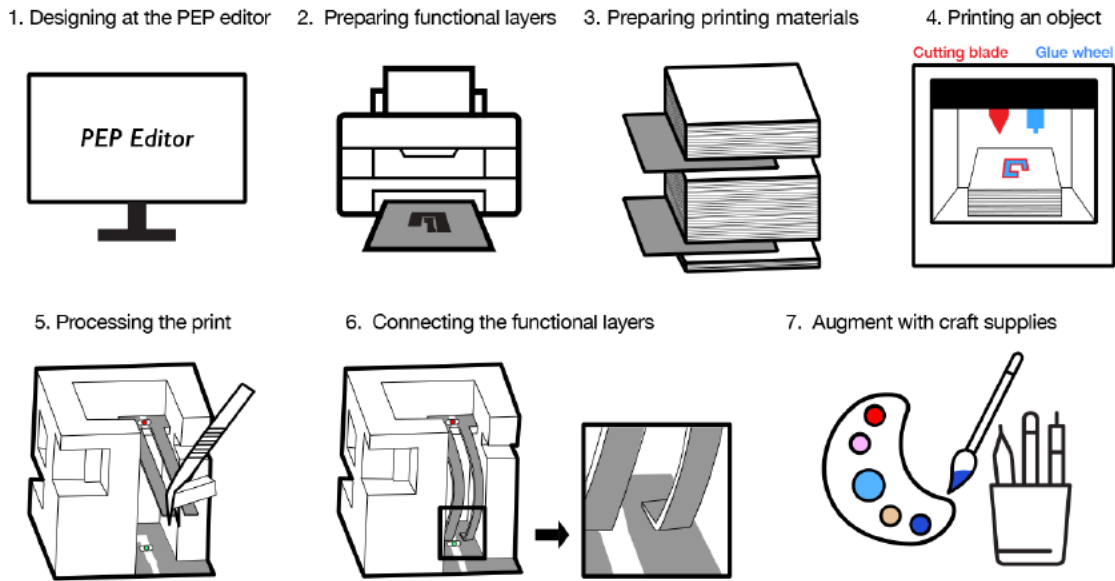
1. Designing at the PEP editor   2. Preparing functional layers   3. Preparing printing materials   4. Printing an object

5. Processing the print   6. Connecting the functional layers   7. Augment with craft supplies

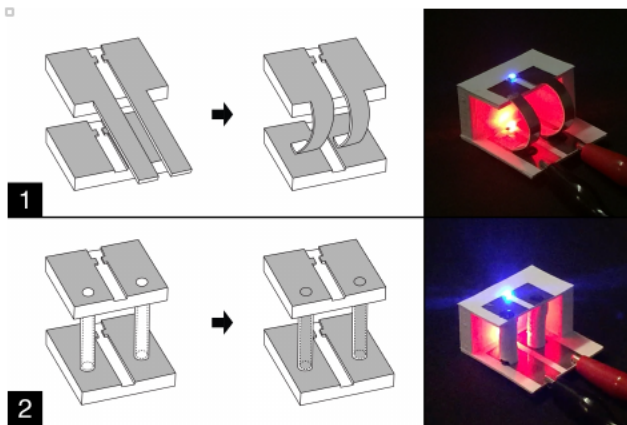**Figure 5. PEP design and fabrication process.**

Figure 6. Two methods to connect multiple functional layers: (1) extending and bending conductive parts (2) carving channels and filling them with conductive material.

PEP FUNCTIONAL PRIMITIVES

We developed four types of functional primitives: actuation, sensing, display, and communication.

Actuation Primitive

Stacking conductive printed patterns during the crafting process enables us to embed actuators into the 3D printed papercraft. We introduce two simple actuators that can be embedded by printing a coil with silver nanoparticle ink.

Heater: A heater can be embedded into the 3D printed product by stacking a conductive ink meander printed resistor between sheets of plain paper. To distribute the heat more evenly in the 3D structure, several silver nanoparticle ink printed coils can be stacked on successive sheets of plain paper. We connect conductive traces on the different layers with conductive epoxy [11] to form a single larger coil-type heater (Figure 7). When a suitable voltage is applied, the conductive pattern generates enough heat to

change the color of thermochromic ink or actuate a phase change pouch motor [23].

Sound Amplification Coil: A printed coil actuates a vibration membrane when embedded into a 3D printed papercraft. When we place the printed object into a magnetic field and connect a signal to the coil, depending on the amplitude of the signal, the magnetic force between the magnet and the coil causes the paper to vibrate and produce sound as a speaker. [15]
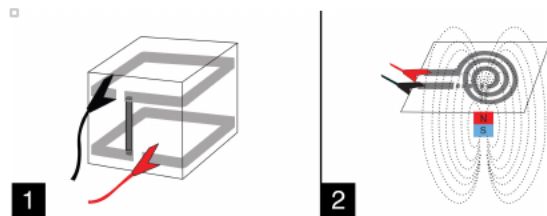

Figure 7. Embedding coils into 3D printed papercraft enables us to make actuators such as a heater (1) and speaker coil (2).

Sensing Primitive

Users can embed various sensors into 3D sculpting electronic papercrafts so that the printed product recognizes changes in its surroundings. We can use existing thin-film sensors or design custom sensors and print them with silver nanoparticle ink.
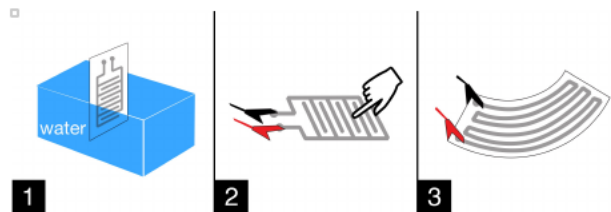

Figure 8. (1) Printed interdigitated capacitors sense the presence of water and humidity, and (2) human touch. (3) A printed resistor can also act as a bend sensor.

Capacitive Sensing: Figure 8 shows our printed capacitive sensor, an interdigitated capacitor. It can sense moisture and also functions as a touch sensor, providing an input channel for users to interact with the finished product.

Resistive Sensing: A silver nanoparticle ink printed pattern will change its resistance responding to an external stimulus. The resistance of a long 'wire' of silver nanoparticle ink changes when we bend the printed substrate. The resistance returns to the initial value when the substrate is no longer bent. Using this property, we can print a bend sensor with silver nanoparticle ink [36].

Display Primitive

Electronic components embedded into a 3D printed product can function as output for the model.

LED: An LED is among the most commonly used elements to display information. After sculpting the product, LEDs can be attached to printed traces using conductive glue.

Electroluminescence: Electroluminescent (light emitting) sheets can be fabricated by silkscreening [24]. We sequentially silkscreened phosphor, dielectric and silver paste layers on top of an indium tin oxide (ITO) sheet [9] to make an electroluminescent sheet. This produces a more subtle lighting effect than LEDs.
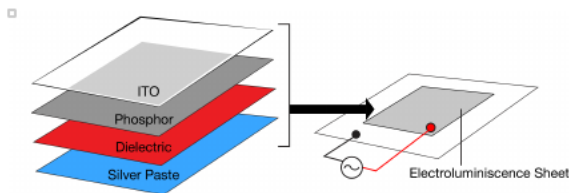
Figure 9. Structure of an electroluminescent sheet.

Communication Primitive

A communication primitive enables 3D printed papercraft objects to interact with other devices.

Radio-frequency identification (RFID): RFID tags, especially thin-film ones, are common in everyday applications such as tracking or advertising. With PEP fabrication, we can easily embed thin-film RFID tags in the stack of plain paper to make the 3D printed papercraft identifiable by an RFID reader.

Wireless Power Transfer (WPT): With the same mechanism of embedding thin film coils into the 3D printed papercraft, we can eliminate a battery or the need for a wired power source. Receiving coils for WPT can be printed with silver nanoparticle ink, (though efficiency will suffer due to the high resistance of the printed pattern - about 0.2 $\Omega/\square$[1]). The silver printing can be strengthened by electroless (chemical) plating on thin-film to obtain low resistance coils [10].

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[1] 1 $\Omega/\square$ - ohm-per-square is the unit used to represent sheet resistance of printed conductive patterns.
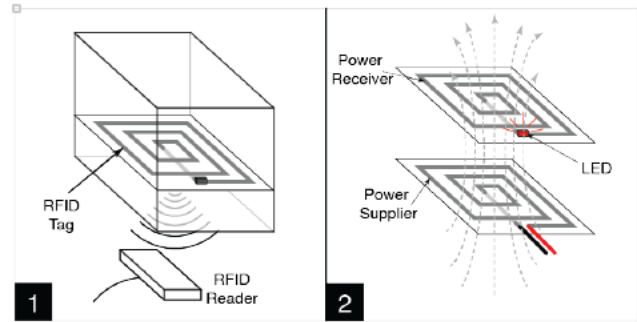
Figure 10. (1) Thin-film RFID tag and (2) wireless power transfer can be embedded.

SOFTWARE DESIGN INTERFACE

We learned through initial prototyping of manual design and fabrication that PEP prototyping requires three different tasks: (1) designing functional layers, (2) integrating functional layers into 3D models, and (3) supporting the fabrication process, specifically file exports, precise measurements, and manual configuration of these parts. We found that the design workflow can be tedious and time consuming, which inhibits free design exploration.

So, to enable users to easily design and fabricate PEP objects, we developed a software tool specifically designed to support end-to-end design of PEP prototypes. The tool introduces two main components: a database for functional components and an interactive editor. The database of functional paper circuits enables a designer to browse and select desired functions without creating from scratch, while allowing the designer to modify the circuit. The interactive editor enables the designer to integrate functional components into an existing 3D model. The editor also provides instructions for fabrication.

Walkthrough

To show how our design tool supports the design workflow, Figure 11 shows a step-by-step walkthrough:

1. Load a 3D model. Select a function component from the database and a surface for the functional layer (Figure 11-1).
2. Apply the functional layer to the selected surface of the model and customize the design of functions (Figure 11-2).
3. More than one functional layer can be applied. Users can connect multiple functional layers to combine them in one circuit (Figure 11-3).
4. Once the user finishes the design process, they can export the functional layers as PDF files well as the 3D model as OBJ/STL files (Figure 11-4).

For the design and integration of functional layers into 3D models, we developed an interactive editor, specialized for the design of PEP products. Most designers prefer to continue using the design software with which they are familiar rather adopting an entirely new editor. Therefore,

we decided to provide our software tool as an add-on to a commonly used 3D CAD tool, Autodesk Fusion 360.

In order to integrate functionality into a 3D model, a user selects components to be applied. As designing reliable electronic functional components can be difficult for designers who lack a technical background, we provide a database of functional components, including circuits for LEDs, switches, capacitive and resistive sensors, and coils. Each functional component is described parametrically, enabling a user to modify and extend designs without sacrificing functionality. The components are designed as two-dimensional sketches. The database is an online repository that designers can browse and select designs from to import into their models. Designers can customize components within the PEP editor as well as design functional components from scratch and add them to the component database. Next, the user selects a face of an existing 3D model to apply a functional layer. Currently, the designer can only apply a functional layer to horizontal or vertical surfaces. When a vertical surface is selected, the system automatically rotates the model.
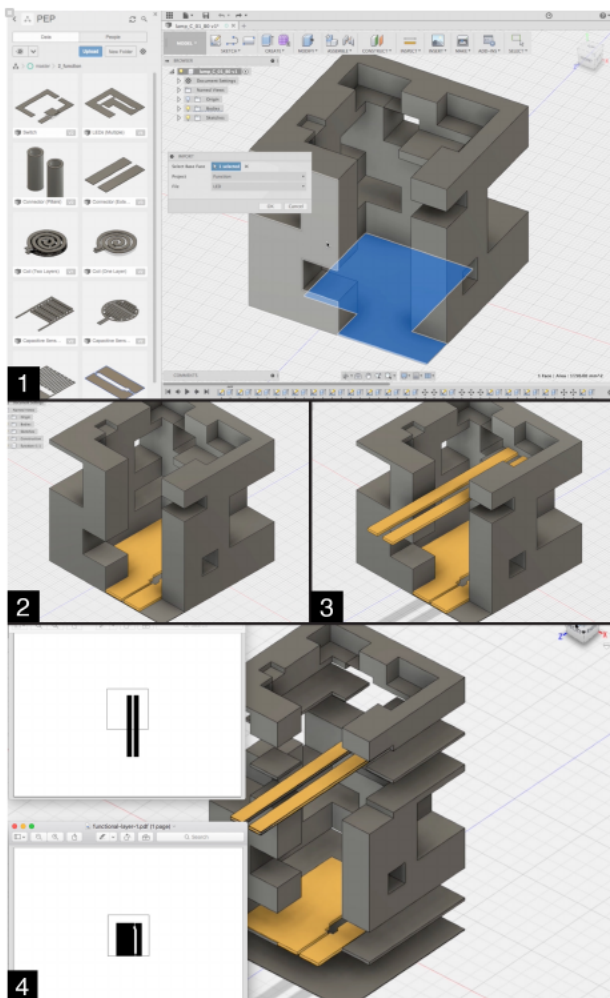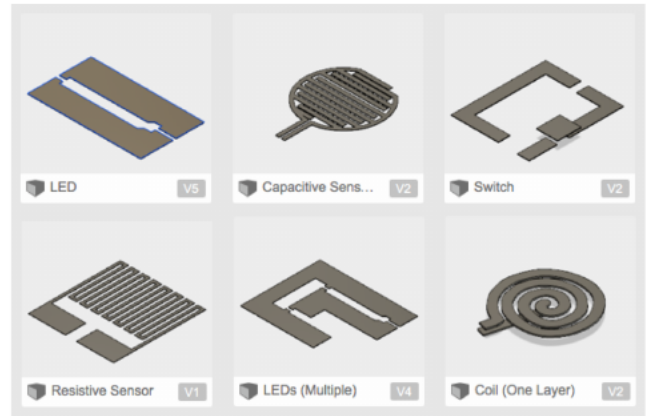

Figure 12. Components in the PEP database.

Once the designer selects a face, the editor automatically inserts the functional layer into the selected horizontal or vertical surface. The user can interactively change the design and parameters of inserted layers by direct manipulation. To add layers the designer repeats the workflow outlined above. To connect layers, the user can choose from two methods: connecting with a conductive channel or pillar or bending the sheets with conductive traces.

After completing the design, the designer exports the functional layers and the modified 3D model as PDF files and STL/OBJ files respectively. To support the following fabrication stage, the software provides guidelines, such as where in the paper stack to insert the functional layer(s) and the horizontal offset of the printed circuit.

EXAMPLE APPLICATIONS

To illustrate the breadth of possibilities of the PEP editor and fabrication techniques, we built eight prototypes for functional layer integration: four *display* examples using LEDs and electroluminescent sheets; a *sensing* example using a moisture sensor; and *communication* using a RFID tag, and a *sound actuation* example using printed coils and a *heat generating* coil. Three of these prototypes also illustrate connected multi-layered functional embedding.

### Simple Functional Layer Implementation

Cube lamp

A sculpted 50mm cube lamp demonstrates a printed electronic papercraft with a display primitive, LEDs. It is sculpted from a stack of paper with one functional layer made by printing conductive traces on paper and attaching two LEDs with conductive glue. The LEDs light up when power is connected.

Figure 11. Design of a cube lamp in the PEP editor.
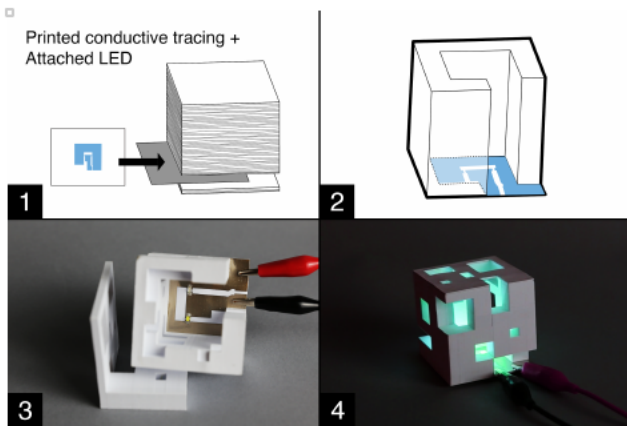
Figure 13. Fabricating a cube lamp: (1) inserting a functional layer with two attached LEDs and printed conductive traces into a stack of paper; (2) sculpting the cube with the Mcor IRIS printer; (3) inside the printed cube lamp; (4) connecting to power to light LEDs.

Architectural model

Architects develop and communicate design ideas with architectural models, and paper is often used to make these models. This application shows how printed electronic papercraft using another display primitive, electroluminescent sheets, can be used in architectural model-making. We attached electroluminescent sheets to 'carrier' sheets of paper, inserted them into a paper stack, sculpted the architectural model, and painted the model with watercolors. When power is connected the windows in front of the electroluminescent sheets light up.
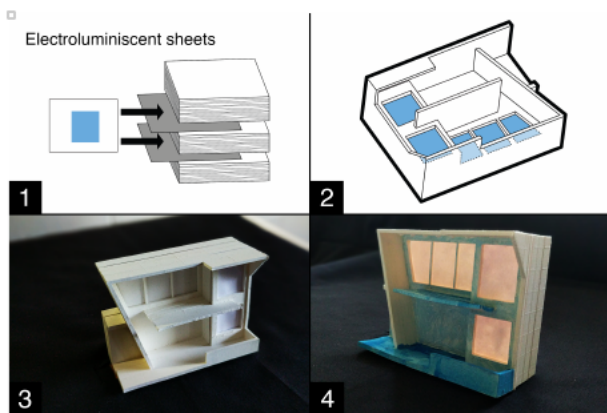

Figure 14. Fabricating an architectural model: (1) inserting two electroluminescent sheets in a stack of paper; (2) 3D sculpting the model; (3) the resulting model; (4) painted in watercolor and equipped with electroluminescent layers.

Photo frame

We can also use an electroluminescent sheet to print a photo frame that illuminates a photo when the surroundings are dark. We included a photo-printed paper sheet and an electroluminescent functional layer in a stack of paper and 3D sculpted a photo frame. When the photo frame is in a dark room, it lights the functional layer to make the embedded photo visible. This application demonstrates

another use of an electroluminescent sheet and combines an image printed paper sheet in 3D sculpting electronic papercrafts.
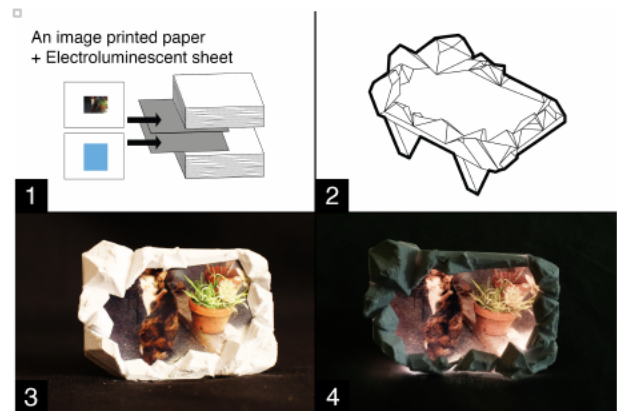
Figure 15. Fabricating a photo frame: (1) a photo printed layer and an electroluminescent functional layer; (2) 3D sculpting a photo frame; (3) the resulting product; (4) lighting the functional layer displays the embedded photo.

Water sensing flowerpot

This flowerpot application demonstrates integration of a sensing primitive into the printing. We produced the functional layer by printing conductive traces, inserted it into a stack of paper, and sculpted a flowerpot. We decorated the pot with colored pens and sealed the inside and outside with two thin layers of Mod Podge [22]. Then we connected the sensing layer to an Arduino microcontroller programmed with capacitive sensing [2] code, showing users when to water the plant. The flowerpot example shows how paper's physical properties can be augmented. Although paper is sometimes seen as a 'weak' medium, depending on design and fabrication we can strengthen paper with post processing techniques.
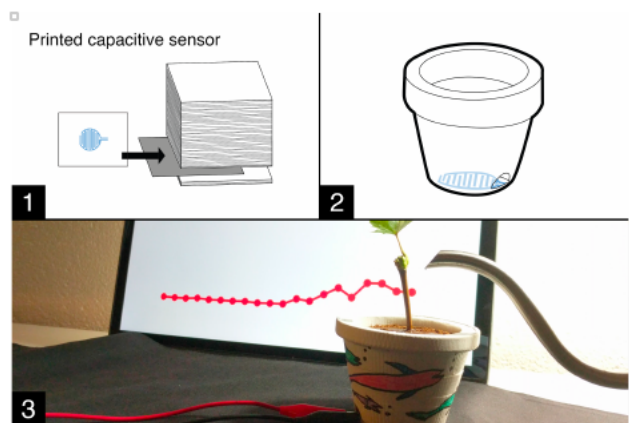
Figure 16. Fabricating a flowerpot: (1) a water sensing layer with printed conductive traces is inserted into a stack of paper; (2) printing a flowerpot with the sensing layer on the bottom; (3) We decorated the printed pot with colored pens. The graph on the screen behind the plant shows soil moisture as we water the plant.
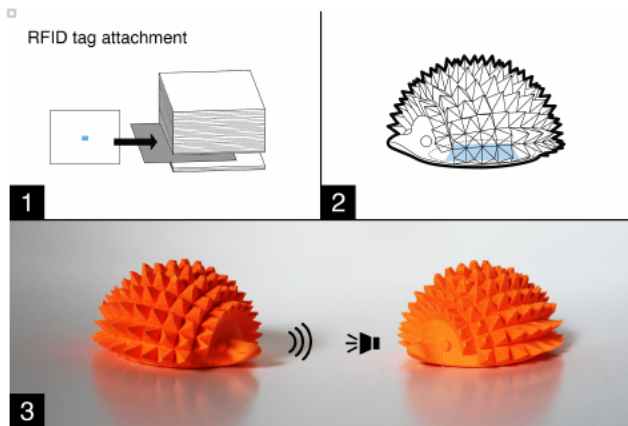
Figure 17. Fabricating a smart toy hedgehog: (1) attaching an RFID tag sticker to a sheet and inserting it into a stack of colored paper; (2) sculpting a toy; (3) a partner toy with an embedded RFID reader senses the RFID tag and plays a melody when it is within 10 cm.

Smart toy

Many electronic components are thin, flat and cuttable, and some can be attached as a sticker without soldering. We made a 'smart toy' hedgehog, inserting into a stack of colored paper one functional layer with an RFID tag sticker. When we place the toy near a partner toy (with an embedded the RFID controller [1] and Arduino microcontroller), the partner toy plays a melody on its buzzer.

Connected, Multiple-Layered Function Implementation

Multicolor cube lamp

We extended the sculpted cube lamp presented earlier to make a lamp with LEDs on different layers. This application demonstrates a method of connecting circuits on different layers by extending and bending the printed conductive traces. We started from the same cube model as the one-color cube lamp. Then, in the PEP editor we added another functional layer and selected the connection method to automatically extend the conductive traces of the upper functional layer. During fabrication, we prepared two functional layers with display primitives: red LEDs for one layer and green ones for the other. We inserted these into a stack of paper, which we used to sculpt a cube lamp. Next we connected the extended conductive traces on the upper functional layer to the lower layer by bending and attaching them with conductive glue. When power is connected, this bicolor lamp lights red LEDs on the upper layer and green LEDs on the lower layer.
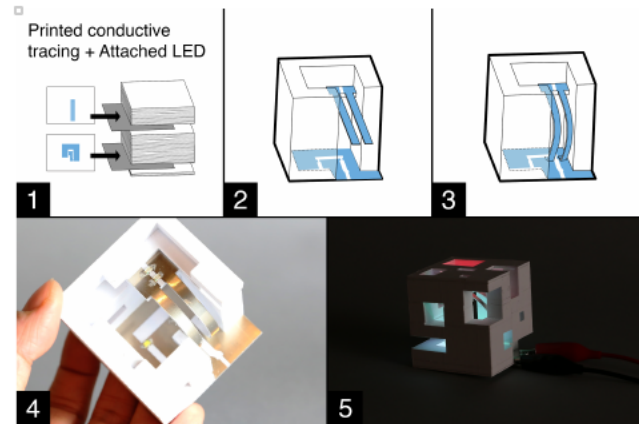
Figure 18. Fabricating a multicolor cube lamp: (1) preparing a stack of paper with two functional layers with different color LEDs; (2) sculpting the form; (3) bending the upper functional layer and attaching it to the lower layer; (4) inside of the lamp; (5) when power is connected, LEDs on both layers light up.

Loudspeaker

This speaker application demonstrates another actuation primitive, a sound amplifying (voice) coil, and a connection method, filling vertical channels with conductive glue. We started by preparing two printed coil layers (a single three-winding coil produces too weak a sound) and a stack of paper for 3D sculpting. After sculpting the form, we connected the coils on two layers with conductive epoxy. In order to reduce resistance of the printed coil by thickening the conductive traces, we printed the coils several times on each sheet. After attaching the coils on different layers, we connected each terminal of the coil to a melody circuit and placed a magnet below.
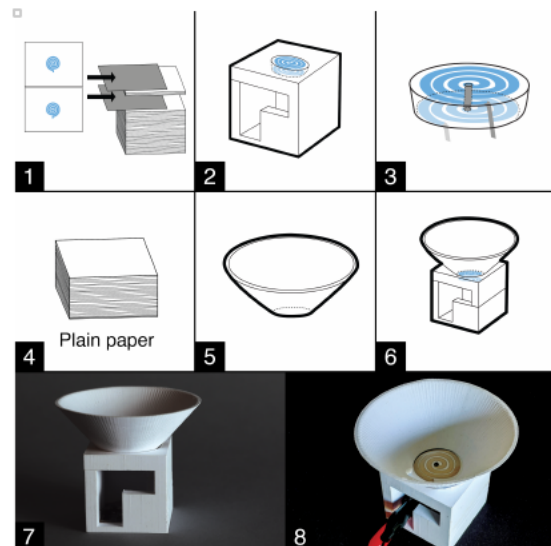
Figure 19. Fabricating a speaker: (1) inserting two printed coil layers into a stack of paper; (2) sculpting a speaker with coils on different layers; (3) connecting coils by injecting conductive epoxy into cross-layer channels; (4) preparing a stack of paper; (5) sculpting a cone; (6) attaching it to the body; (7) the combined model; (8) connecting the coil to a melody circuit.

Color-change cup holder

A cup holder demonstrates a heat generating coil application with thermochromic color change pigments. We developed a cup model in five parts, planning to embed four layers of coils between the parts. Then we printed four coil layers with a stack of paper and 3D sculpted all parts. Using the printed parts, we assembled the parts from the bottom using paper glue and connected the coils with conductive epoxy. Once the cup holder was dried and cured, we painted thermochromic pigments and connected power to see the color changes. The coil resistance was 80Ω and we connected to 12V, therefore the power dissipation was just 1.8W, enough to produce color changes but not to make the surface too hot.
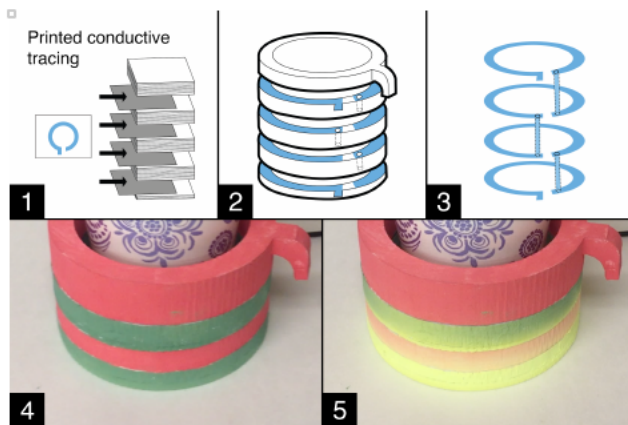
Figure 20. Fabricating a cup holder: (1) combining four functional layers of printed coils with a stack of paper; (2) sculpting five parts of the cup; (3) connecting the coils by injecting conductive epoxy into the cross-layer channels; (4) the applied thermochromic color without heat; (5) color changes when the power is connected by heat generation.

LIMITATIONS AND FUTURE WORK

Our PEP techniques have unique limitations; this leads us to propose a call for future work:

- The Mcor IRIS printer for 3D sculpting constrains the size, thickness (weight), and texture (slipperiness) of material. We can only load US letter (or A4) paper under 20lb weight; otherwise the printer fails to transport sheets from the stack to the build platform. If the material is too slippery (e.g., OHP film) the printer fails to grab sheets or properly adhere layers; even one poorly attached layer impacts the accuracy of cutting and attaching successive sheets. Therefore, we glue electroluminescent sheets to a 'carrier' sheet of paper. Future printers may resolve these technical issues. To enhance the affordances of PEP techniques, these two constraints need to be addressed in the next version of the printer development.
- Printed electronic papercrafts can be fragile depending on the design and placement of the model on the build platform. The printer creates 3D objects by gluing and cutting many flat sheets of paper. Therefore, a product

that includes thin and long vertical parts (approximately less than 3mm) is fragile. Likewise, we cannot bend or fold printed parts if the attached paper sheets are placed vertically.

- Our actuation primitives include only examples of heat and sound actuation. In the future, we can obtain mechanical actuation by adding thin film actuators such as actuated paper hinge that can be inkjet printed as for example in Foldio [25].
- Regarding the density of conductive layers, currently we support only single-sided conductive layers, so paper thickness governs density. In the future, we can adopt the double-sided conductive layer by via-hole techniques [34]. This can help to increase the density of conductive layers stacked into the model; two facing layers must be insulated by non-conductive coating.
- Although the PEP editor indicates where to embed functional layers in the stack of paper, we must count the number of layers to insert functional layers at the right position, which can be tedious and inaccurate. A counting error results in misplacing functional layers. We plan to address this by modifying the PEP editor to connect it to a printer to count the number of paper in forming the paper stack.
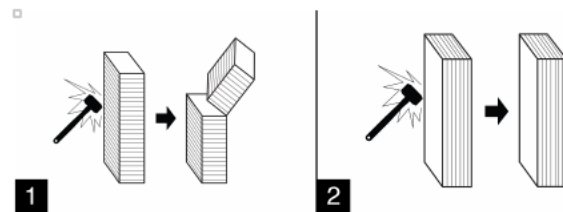
Figure 21. Designers must consider model orientation in the printer. Structure 1 is more fragile than 2: (1) horizontally attached sheets and (2) vertically attached sheets

CONCLUSION

We introduced printed electronic papercrafts by 3D sculpting. Leveraging electronically enhanced papercrafts with 3D sculpting can enable new creative possibilities and we presented a set of fabrication techniques with a design editor to afford such prototyping using today's technology. By inserting functional layers into a stack of plain paper, we can develop interactive 3D paper prototypes by cutting and gluing sheets of paper. Our software supports designing the integration process with a set of functionality (actuation, sensing, display, and communication). We believe the unique affordances of paper prototypes can be further extended, and in this paper we explored and demonstrated what's possible today by combining paper with electronic components and leveraging such combination with 3D sculpting.

ACKNOWLEDGMENTS

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