Interactive Paper Devices: End-user Design & Fabrication

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ABSTRACT
We describe a family of interactive devices made from paper and simple electronics: Paper Robots, Paper Speakers and Paper Lamps. We developed construction techniques for these paper devices and the Paper Factory software with which novice users can create and build their own designs. The process and materials support DIY design and could be used with low-cost production and shipment from an external service.

Author Keywords
Paper computing, evolutionary design, co-creation

ACM Classification Keywords
H.1.2 User/Machine Systems; J.5 Arts and Humanities (Arts, fine and performing); J.6 Computer-aided engineering (computer aided design)

General Terms
Design, Experimentation

INTRODUCTION: TOOLS FOR END-USER DESIGN
We are witnessing a shift in the roles of producers and citizens, in which people formerly known as "consumers" are increasingly becoming innovators [1, 2]. The trend toward co-creation, or end-user participation in design began decades ago. The 1970s brought the custom-printed T-shirt, coffee mug, and wall-poster, obtained via mail-order or made locally at a specialty store. The advent of the desktop printer and publishing software in the 1990s significantly lowered the time, effort, and money needed to create expressive content on paper. Today new computer-aided manufacturing (CAM) tools such as laser cutters and rapid prototyping printers are expanding custom production from 2D to 3D.

The Internet supports this phenomenon by enabling people to share designs online as well as to outsource fabrication. Websites such as instructables.com and makezine.com are active communities for sharing product ideas and supporting contributors. Other sites such as Shapeways.com and Ponoko.com produce custom items on demand. They occupy an interesting market niche, leveraging the fact that digital fabrication equipment, although substantially less expensive than mass-production machinery, is still too costly for casual use. These services enable novice designers (i.e, people without technical or design training) to specify and manufacture products.

Although digital manufacturing tools make it possible to produce customized objects, there are limitations in what can be readily made. Each manufacturing process and each material requires knowledge—sometimes highly technical knowledge—of these limitations. To take advantage of digital fabrication methods and make good products, designers must know (sometimes quite arcane) software, be familiar with (sometimes subtle) material properties, and understand the (sometimes tricky) fabrication process.

The online co-creation services mentioned above address these challenges in various ways. One approach is to severely limit the design space, guiding users through a sequence of choices [4]. This strategy ensures that users can create only manufacturable designs, but it also sharply

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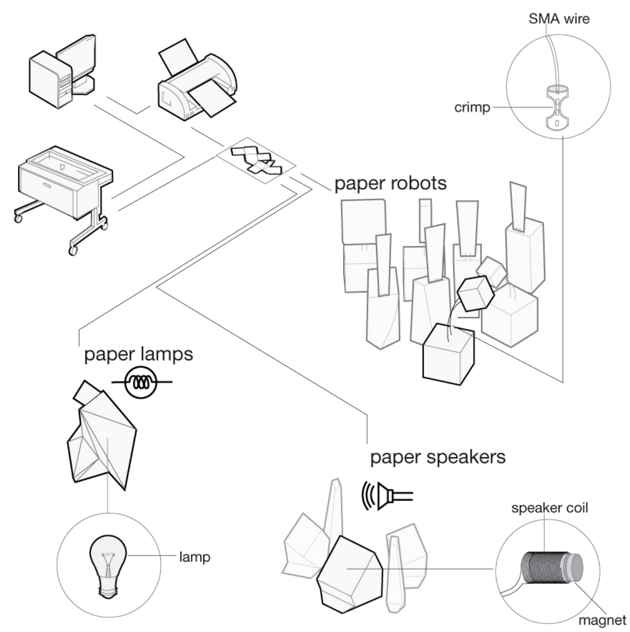

Figure 1. Design and fabrication of interactive paper devices.

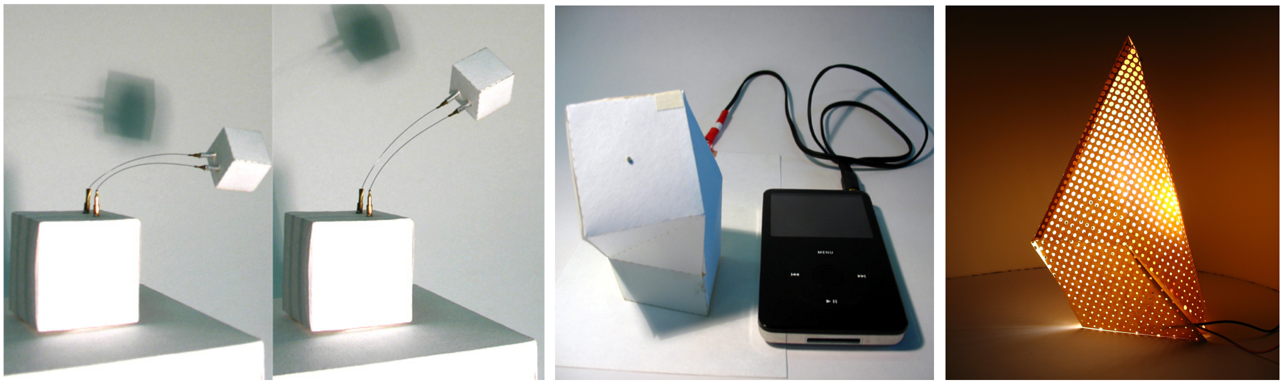

Figure 2. Three kinds of paper devices: Left: Paper robot "Sleepy Box". Center: Paper Speaker. Right: Paper Lamp.

restricts their creative role. At the other extreme, professional services for manufacturing highly technical products (such as printed circuit boards) allow a much wider range of choice, but designers assume responsibility for the outcome. High-end digital fabricators provide design rule checking, either in custom software to prepare files or through automated checking of submissions. Checking verifies that a product can be manufactured but does not help the designer to achieve higher-level goals. Although this is appropriate for experienced designers, DIY designers require and appreciate more support. Our challenge is to strike an appropriate balance between giving DIY designers control and ensuring that they obtain results that match their expectations.

We begin by describing three varieties of paper devices that illustrate the scope of our design and manufacturing domain. Then we outline the materials, components, and fabrication process employed to make these products (Figure 2).

We next describe the Paper Factory computational environment, used to design 3D objects from paper by employing an evolutionary design method. We conclude with a discussion of how this particular set of materials and methods points at more general themes in DIY design and manufacture of interactive objects and a list of directions for future work.

Figure 2 shows three kinds of paper devices we have made: All employ similar materials and construction; each highlights different aspects. *Paper robots* emphasize interaction and physical actuation; *paper speakers* illustrate how non-visual attributes such as sound can be features of a paper device; and *paper lamps* emphasize the physical form, aesthetics, and visual effects.

Paper Robots

Paper Robots are little playful toys that use Nitinol shape-memory alloy (SMA) wires and embedded electronics to move and interact with people. Their bodies are made from paper folded into cubes of varying size. What makes them different from many popular paper craft kits (for example, paper robot models from readymech.com, piperoid, or gagatree) is that our robots are animated by SMA wire that connects parts of their paper bodies. Changing the size of paper parts, the length of SMA, and the connector type, gives the robot a unique motion. The Sleepy Box robot in Figure 2 (left), for instance, has a long "neck" made from SMA wire that can raise or lower its "head".

The robot snaps magnetically to a paper Base Box that contains a microcontroller and support electronics that powers and controls the robot. We use an Arduino for prototyping; a standalone PIC or Atmega chip would also serve. By programming the microcontroller, we give paper robots different behaviors. The Sleepy Box in Figure 2 left is programmed to fall asleep and nod its head, but wakes up when people clap or yell at it. When awoken, the Sleepy Box dances by bobbing its head up and down to a clapped beat. In another version, Sleepy Box connects to a PC and responds to online chat connections, indicating physically when one of a user's buddies is online.

Paper Speakers

Paper Speakers plug into any device with a headphone port and plays sounds (Figure 2 center). Unlike the typical solid black box speaker, paper speakers are light and fragile. The construction is simple: A copper coil is hand-wound around a neodymium magnetic core attached to one face of a paper box. The paper shell acts as a diaphragm and the oscillating magnet produces a visible and audible vibration. Varying the shape and paper quality causes each speaker to resonate differently.

Paper Lamps

A Paper Lamp is a paper shell with patterns cut into its surface and a light bulb inside (Figure 2, right). The shape of a paper lamp results from an interaction between initial criteria set by the designer, the physical constraints of paper, and the user's preferences expressed dynamically by selecting among system-generated alternatives. Experimenting visually with patterns on the lamp allows the designer to further individualize the design.

MATERIALS AND METHODS OF CONSTRUCTION

We now introduce the specific materials and components used to make paper devices, and the fabrication methods we developed to work with these materials and components. The main materials are paper, SMA wire, copper tape, and gold leaf foil; we also use thin wire-wrap wire, conductive glue, copper foil tape, and small neodymium magnets. The main construction techniques are cutting, folding, and gluing. We also developed methods for specific details such as connecting the ends of nitinol wire electrically and physically to the paper devices.

Paper

Our designs take advantage of paper's properties; it is light, translucent, flexible, readily available, and can be simulated computationally. Designs made from paper can be cut with computer controlled laser cutters or by hand—we have used a laser cutter, a desktop CNC card cutter (e.g., CraftRobo™), as well as X-Acto™ knives. We have experimented successfully with a range of paper types with different material properties, from diaphanous rice paper to robust plasticized card stock. Most papers can be easily printed with an inkjet or laser printer as well as painted or coated by hand with various inks and dyes. For example, we painted one paper lamp with thermochromic ink, which changes color, revealing heat distribution within the lamp body. We also laser-etched patterns onto the internal faces of some lamps, which appear when the lamp is lit.

SMA Muscles

On account of the fragility of paper we avoid heavy components. We use nitinol SMA wire to provide actuation, gold-leaf circuits to connect components, and embedded electronics to provide interactive behavior. Nitinol wire is easily actuated using an embedded computer and controlled with a square wave PWM (pulse-width modulation) signal. It is commonly used in robotics [5] and can be embedded into other materials [6]. The 0.008" nitinol wire we used is light and adds little weight to a product (Figure 3). As wire is a material—not a discrete component—we can vary its length and form to predictably achieve desired results. These results are computable, as resistance per inch is proportional to force exerted at different voltages. This allows us to simulate the nitinol wire's behavior using a physics engine. We investigated two methods of using nitinol wire to actuate paper devices. Each method had different advantages, weaknesses, and applications.

Nitinol Flex Neck

The flex neck uses nitinol wire in 'positive' and 'negative' pairs, approximately 15mm in length, to link two paper elements (as in Figure 2 left). When powered, the wire straightens, lifting one paper element (the head) into the air. Gravity returns the head to its down position when the wire is not powered, eliminating the need for counter springs. A microcontroller controls the extent of movement by pulsing the wire. Using nitinol wire this way provides several benefits: Muscles can vary in length and placement, which allows for an open design system; and because only nitinol wire and a crimp are used, this joint is relatively inexpensive. The muscle is light, like the paper, and people find this material and its movement novel and intriguing.

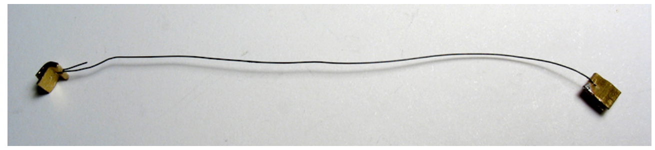

Figure 3. A small SMA muscle. It is approximately 7cm (3") long and made of .008" nitinol. At each end the wire is terminated with a clip made of crimped brass tubing.

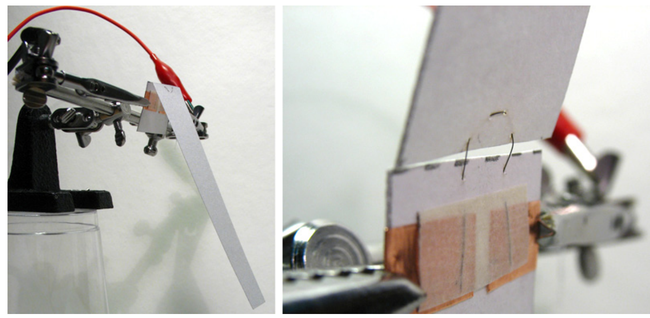

Figure 4. SMA wire hinge is sewn between two pieces of paper, using copper adhesive tape for contacts.

SMA Paper Hinge

This method consists in sewing a small length of SMA wire into two adjoining pieces of paper to make a hinge (Figure 4). This method provides a quick and simple method for obtaining movement at a joint as it requires no crimps and uses very little wire. It is also a reasonably power-efficient method of obtaining movement.

Clips and Crimping

Nitinol wire functions both physically, as an actuator and electrically, as a conductor. To attach the wire to the paper bodies we designed a strong conducting clip that is inexpensive and easy to use. It consists of a small strip of brass plate crimped around the nitinol wire. We heat the clip to set the wire in a shape that prevents it from wiggling free from the crimp during use. The end of the crimp is formed into a clip that allows the muscle to be easily attached to the paper shell at electrical contact points.

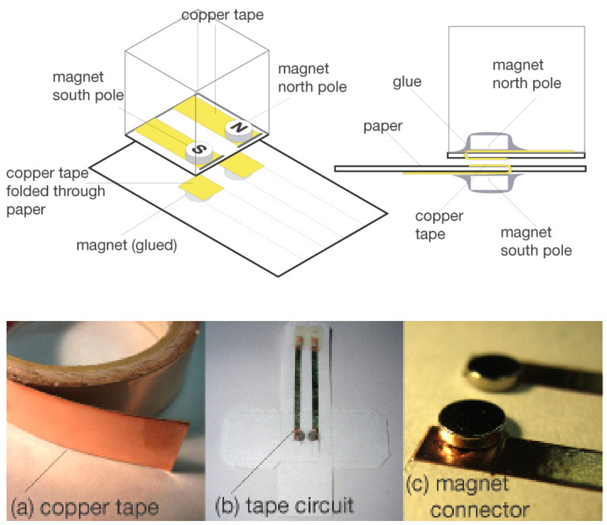

Figure 5. Magnets on either side of a paper sheet form an electrical connection with copper tape.

Magnetic Connector

We designed a simple magnetic connector to make an easily detachable electric connection between two parts—for example, to connect a paper robot with its base box. We used neodymium magnets that are small, relatively inexpensive, and strong. The contact surfaces of both parts are conductive copper tape. On the other side of each paper part behind the tape is a disc magnet; the attraction between the magnets presses the copper tape contacts together (Figure 5). The connection is also uni-directional: When the two paper parts are placed incorrectly the magnet pairs repel each other.

We also use magnets in the paper speakers for their electromagnetic properties. The speaker coil is copper wire-wrap wire wound around a neodymium magnet. It is either glued directly to the paper shell, or a smaller second magnet is used on the opposite side of the paper to hold the coil magnet in place (Figure 6).

Gold Leaf Circuit Paths

Even conventional electrical wires are too heavy for nitinol-actuated robots. Therefore we developed a method for constructing circuits directly on paper. We are aware of efforts to adopt inkjet technology to directly print conductive paths on paper (e.g., [8, 9]) but these have not yet matured; another DIY option is to hand-paint the circuits on the paper [10,7]. Our method allows greater precision and repeatability, and better integration into the computational design environment. The circuit shown in Figure 7 was made by spraying adhesive through a laser cut stencil, and then applying gold leaf to the adhesive traces and brushing the remainder away—a process similar to gold leaf gilding.

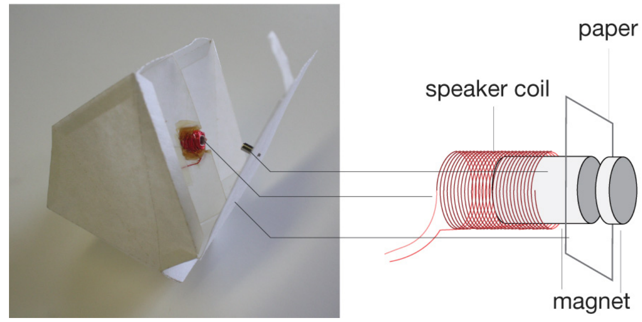

Figure 6. Hand wound coil around a neodymium magnet attached to a surface of the speaker's paper shell. A second smaller magnet on the other side of the paper holds the coil in place. (top – schematic diagram; bottom – photo).

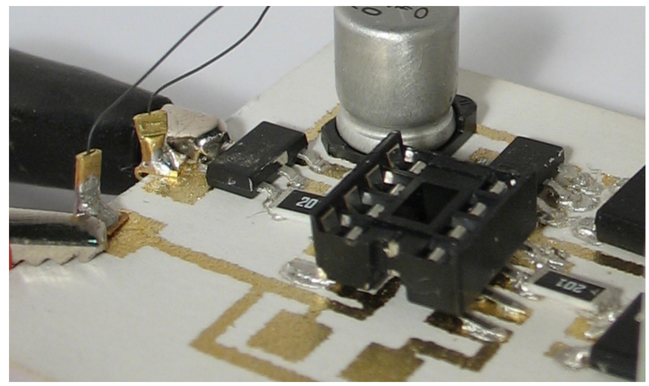

Figure 7. Gold leaf circuit with electronics for controlling an SMA wire and rectifying external AC power; note SMA wire with copper clips.

We attached components to the circuit using conductive glue; brass clips connect the paper circuit with external components such as the power supply and muscles.

THE PAPER FACTORY DESIGN ENVIRONMENT

We turn now to the Paper Factory evolutionary design environment, a Java desktop application that we built to produce paper devices. Paper Factory is similar to other software, Pop-up Workshop, Javagami, and PePaKuRa. These have been made available online to help user craft polyhedral 3D objects[11-13]. They are based on algorithms that unfold surfaces that compose 3D shapes onto 2D patterns[14, 15]. We equipped Paper Factory further with evolutionary and genetic algorithms, a powerful technique to rapidly generate and test designs [16-18]. Paper Factory's evolutionary algorithm can be used in two ways: (1) to automatically produce designs that solve a set of physical constraints; (2) as a tool for the human designer, augmenting the design process. In the latter, interactive, process, designs begun by hand can be evolved to provide alternatives, and the designer can guide the evolutionary process by selecting designs for continued evolution. Figure 8 shows a screen snapshot of the Paper Factory program, with a series of evolving designs in the

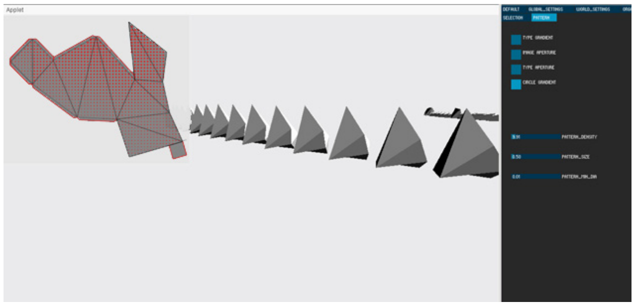

Figure 8. Paper Factory user interface showing unfolded pattern (top left), population of evolved forms (center), and parameter controls (right).

center; the rules control panel at the right, and an unfolded design in the inset window at the left.

A designer begins with an initial 3D model loaded from an STL file or (in the examples shown here) simply with a cube. At each design iteration a 3D model of a candidate design is generated (either by the user or automatically by the program), its physical properties are simulated, and it is either retained or discarded by the natural selection module.

At each stage, the designer can develop the form of the design by making changes to the geometric model by hand or by applying the 'evolve design' option. When the designer requests evolution, Paper Factory iteratively varies the design, placing each 'child' variation next to its parent. The program subjects the design to a physics simulation to determine how it would behave, e.g., whether its structure would fail if made from paper. Additionally, the design is tested against a list of designer-specified rules such as: Am I taller than my parent? Do I use less material? Can I stand? Could I be produced? A design that passes these tests is kept and a new iteration is made. For example, the lamp in Figure 9 resulted from a fitness function set to grow a taller lamp whilst wasting the least paper.

The designer can turn rules off and on to influence the evolution of the final form. If a design has desirable or interesting attributes the designer can select it and instruct the application to make tangent iterations or evolutions. A desirable form can be selected and the unfolded pattern exported to a PDF file for printing.

IMPLEMENTATION

Figure 10 shows the organization of the Paper Factory system, including the main data structure (paper organism) and several modules that operate on it.

Paper Organism

The Paper Organism is the main data structure that holds details about a specific design. It includes two copies of the 3D model. The first is subjected to simulated physical forces, then tested. The second is used as the 'genetic material' for the natural selection algorithm to generate new forms, as well as for producing paper cut patterns. The second copy of the model is needed because the physics simulation distorts the mesh of the first model, which would cause errors in the paper cut form.

Physics Simulation

The system uses a particle based Verlet integration physics simulation[19] (http://code.google.com/p/toxiclibs/) to model the material properties of paper and the nitinol wire. The simulation operates on the 3D model in the Paper Organism data structure. The simulation tests the movement of an object under gravity and its structural integrity. Simulated particles are placed at each vertex of the 3D form joined by rigid spring constraints at each edge. If a rigid edge compresses to a parameterized limit due to a large force, the edge is broken and removed from the simulation, approximating a piece of paper folding under pressure.

Natural Selection

The Natural Selection module tests each design against a set of rules to determine its fitness. Rules are based on physical characteristics gathered from the design's mesh after it is subjected to the physics engine. Virtually testing different attributes of an object before building them enables us to generate design variations and then test resulting designs against selection criteria to see whether any new design performs better than its parent. The program then iterates on that design until an even better solution is found.

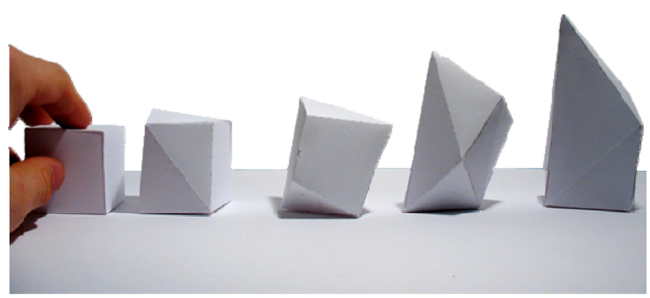

Figure 9. A sequence of evolved forms. The design criteria were: tallest form, stable structure, and minimal waste.

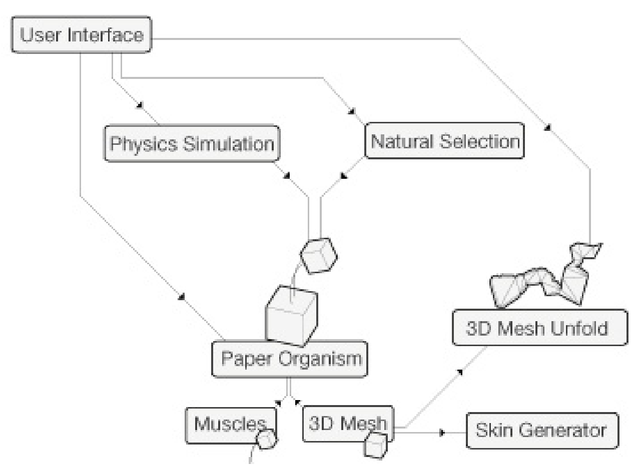

Figure 10. Paper Factory System architecture

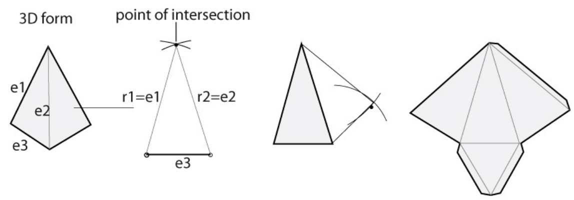

Figure 11. 3D model to 2D pattern.

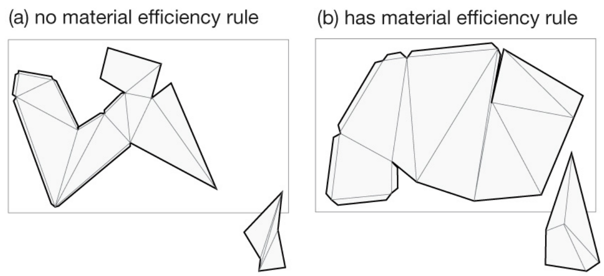

Figure 12. The unfolding algorithm can optimize the material.

3D Mesh Unfold

The 3D Mesh Unfold module extracts a 3D mesh from the Paper Organism, unfolds it into a flat 2D pattern and adds fold lines and tabs for gluing. The pattern can then be rendered to the screen or to a PDF file for printing and cutting.

The 3D Mesh Unfold module triangulates the 3D model, then selects and projects each triangle onto a 2D plane. It uses the length of three sides of each face and a circle-circle intersection to place the projections on the plane (Figure 11). It does this recursively for all combinations of patterns to find the most space-efficient method of unfolding the 3D model onto the 2D surface. As the 2D unfolded pattern may overlap itself, resulting in an un-makeable pattern, the unfolding algorithm checks for this and selects only patterns that do not overlap. If a non-overlapping pattern cannot be found (which is often the case in complex models) then the algorithm breaks the pattern into multiple pieces. The designer can also instruct the program to minimize wasted paper (Figure 12). Finally, the program adds tabs to the pattern for gluing together the paper model.

Skin Generator

The Skin Generator module applies a graphic pattern onto the surface of the 3D model and the 2D unfolded pattern. It first applies a pattern to the unfolded 2D pattern, then skins the 3D model using UV mapping. Patterns relate to the geometry of the model and may be parameterized by 3D position. For example, the circles in the pattern of the lamp in Figure 2 (right) increase in size the higher they are, producing a lamp in which more light spills from the top than the bottom.

The system produces a flat pattern used to construct a design, so it can calculate how much material is needed for each design as well as how many edges will need to be folded and how many glued. These attributes, too, may be used as a selection criterion to evaluate a design's fitness. The system can thereby find designs that are more efficient in material and labor.

DISCUSSION

We have presented designs, construction techniques and custom software that support a user in designing their own interactive paper products. The Paper Factory simulates the physical behavior of designs, tests for manufacturability, cost, and viability, and employs an interactive evolutionary algorithm to generate design alternatives shaped by end-user preferences. Such as system could be useful to support end-user design, both for DIY makers as well as in commercial mass customization, where a manufacturer must calculate the cost and viability of a design before selling it.

We developed and refined the techniques described here to experiment with a family of interactive paper devices. We have used them to make paper lamps, paper robots, and paper speakers for our own entertainment, and as gifts for friends and family. Overall we have made approximately one hundred experimental devices. Although we have successfully included making paper devices as an exercise in a class on physical computing, we have not engaged in formal user testing of these techniques. Our experience has convinced us that our techniques are viable, and that the interactive evolutionary design process can be easily managed without requiring of users a detailed understanding of the underlying constraints.

We have described three branches of the paper device family as distinct; this reflects the sequence of our own explorations of this territory. Clearly, however, this distinction is artificial– the techniques we used to evolve paper lamps could be used to evolve paper speakers (using a physics simulation of sound properties as a fitness function), or to evolve paper creatures that use SMA wire to obtain particular characteristics of locomotion in the manner of Sims's Evolved Virtual Creatures [18].

The particular technical universe we have explored—paper, magnets, SMA wire, gold foil and copper tape—seems appropriate for making interactive devices today. We used this technical universe to explore ideas about computational design environments for novice and end-user designers. However, we anticipate that with advances in rapid manufacturing, these ideas will have broader applicability. As desktop manufacturing becomes more capable, the need will only grow for the means for end-users to specify designs through an interactive process that guards them from error, yet provides control and flexibility over materials and manufacture.

FUTURE WORK

User-defined rules

The present Paper Factory system does not provide end-users with the means to easily describe new evolutionary selection rules. Rules must currently be hand-coded and added to the software. Once a rule has been coded, however, an end-user may select it and apply it to the current design process. One avenue for future work is to develop an interactive way for designers to specify design rules without resorting to hand-coding in Java.

We have also not discussed the process by which a designer programs a paper device. In our current scheme, the designer must either adopt an existing microcontroller program or write a new one from scratch. In another related project we explored the use of finite state machine diagrams to program the behavior of interactive devices; we plan to incorporate this into the Paper Factory.

Site-specific evolution

So far all the Paper Lamps we've made evolve on a flat plane. However, a richer variety can be achieved if we add to the simulation the specific site where the lamp is to be used. The lamp form would then evolve to suit the environment for which it is designed; for example, to produce a paper lamp that fits specifically on the end-user designer's shelf and shed light on designated table area.

Identification Barcodes

Each paper device is the result of a hybrid direct-manipulation and evolutionary design process. The resulting product can be described by a set of parameters that uniquely identify it. We have begun to investigate printing optically readable (e.g., barcode or QR-code) tags on each paper device. This would enable people who encounter the device to read or scan the code with cell phone, and obtain the digital DNA. The DNA could then be used to clone itself or as a starting point for further evolution.

SMA wire Simulation

Among the material we employ in the paper devices, SMA wire is relatively less explored and documented. We plan to help user design the motion of a paper device by simulating the SMA wire. This can be done by adding constraints to the physics simulation. The SMA hinge joint is presented as two faces connected at one edge—as the virtual hinge is powered, forces are applied to the two faces, rotating them about the connected edge until they become parallel. The flex neck is simulated in a similar manner, except that the two edges are connected using an additional face that holds the two powered faces apart.

Locomotion of paper creatures

We have been pleased with using SMA wire in working with lightweight material like paper. It produces an organic motion that differs greatly from that of electrical motors. Our current technical vocabulary of SMA wire is limited to the flex-neck and hinge mechanisms. However we plan to investigate other locomotion patterns for paper products.

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