

Easigami: A reconfigurable folded-sheet TUI

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ABSTRACT

Easigami is a novel tangible user interface (TUI) and interactive system intended to help children to learn to fold 3D geometric forms and to explore 2D-3D transformations. We present the design of *Easigami*'s physical interface: a reconfigurable system of thin flat polygon pieces connected by electronically instrumented hinges. Using the *Easigami* TUI as an input device, we have developed early prototype applications to develop children's visualization and spatial recognition skills. We discuss our experience in integrating traditional craft with computation, which may inform future tangible and graspable user interface design.

Author Keywords

Origami, folding, 2D-3D transformation, tangible user interface (TUI), interaction design, spatial visualization ability

ACM Classification Keywords

H5.2. [Information interfaces and presentation]: User Interfaces – Haptic I/O, Input devices and strategies, Prototyping.

INTRODUCTION

Computationally Enhanced Construction Kits and Craft

Inspired by origami – the art of paper folding – we designed *Easigami*: a novel tangible user interface (TUI) and embedded interactive system. Whereas traditional origami uses a piece of intact square paper, *Easigami*'s physical interface is composed of thin flat polygon pieces and electronically instrumented hinges that can be assembled to behave like a foldable sheet. The hinges join polygons to form flat patterns with predetermined creases. Each hinge senses the dihedral angle between its two adjacent polygons and sends this information to a computer.

Easigami's polygon and detachable hinge design makes it a *reconfigurable TUI*, or TUI construction kit. The space of configurations that *Easigami* supports is highly constrained, restricted to folded sheets, but the design of the hardware-software ensemble echoes traditional (non-computational) construction kits, which consist of physical components

and the means to assemble them.

Two steps are required to use the *Easigami* tangible user interface. First a user configures a 2D sheet TUI by connecting polygons with hinges, and then, using the *Easigami* 2D Pattern Builder, tells the software how the sheet is configured. Once the user has constructed the folded sheet TUI and registered this pattern with the software, *Easigami* monitors and maintains the model as the user folds the polygons into a three-dimensional form. Figure 1 shows how the *Easigami* 3D Form Explorer displays a 3D model on the screen in real time.

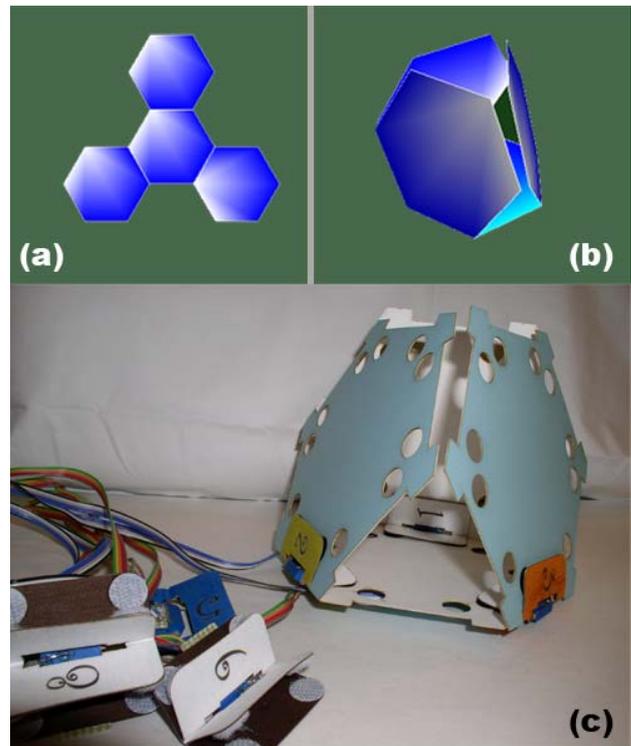


Figure 1: Folding a Truncated Tetrahedron - (a) 2D digital pattern; (b) 3D digital model; (c) Physical model using the *Easigami* TUI.

The design follows our conviction that construction and craft play offer outstanding opportunities for learning [1-3]; and providing a rich palette of materials will create powerful learning opportunities for children that transcend any specific learning objectives [4-8]. This constructionist approach has led to our design of the reconfigurable TUI of *Easigami* – a kit of hinge parts and polygons that can be

reconfigured to make different variations of the folded-sheet TUI.

Folding in Design and Education

Origami is a design system that is at once highly constrained and open-ended. It is highly constrained: its only design move is the fold, and folds can be made only in certain ways. Yet it is open-ended: implicit in the origami system is a rich universe of alternatives.

Folding is among the methods that artists, designers and engineers use to create 3D structural forms. Origami techniques are used to create products such as fast-food containers, lamps and furniture. A recent trend in architectural design deploys folded surfaces in making buildings – illustrated by the Yokohama International Port Terminal [9]: “The technique of folding makes it possible to re-appraise every step. Each step is laden with potential.” [10]. Formal study of origami is also contributing to various fields of science and engineering, for example, in the design of engineered structures, in computer science, robotics [11] and in modeling complicated spatial forms in biology such as the structure of proteins [12].

Paper folding occupies an interesting spot between mathematics, craft, and art. Like all three-dimensional design problems, skillful folding requires spatial reasoning ability. Easigami provides a construction kit and a playful activity with which children can improve their spatial reasoning skills by practicing 2D-3D transformations and observing the synchronized graphics when manipulating the Easigami kit [13]. One study suggests that origami training affects brain development [14].

RELATED WORK

Paper folding, and in particular, origami, is a typical traditional craft activity for children and adults. Various projects have augmented paper folding with computational media. Some take a CAD-CAM approach; for example, Ann and Mike Eisenberg’s Hypergami system provides a computer-based workshop for making sculpture from folded paper polyhedra [15]. The sculpture is designed and decorated on screen, then printed, cut, and assembled by hand. Jun Mitani’s Oripa [16] and Pepakura [17] are in the same CAD-CAM vein. Others take an “external sensing” approach: Mitani and his Tskuba colleagues also developed a system that uses a digital camera to read QR-codes pre-printed on the folding paper [18] and then employs this information to infer the three-dimensional form as the user folds the paper.

In contrast to these approaches, our Easigami project takes an embedded computing approach to integrate computational media with paper folding. Easigami embeds sensors into the materials of construction, so that the tangible user interface constructed by a set of hinged polygons can determine what the user is doing with it. Other computationally enhanced construction kits that employ embedded sensing include Topobo [19], Computational Building Blocks [20, 21], ActiveCube [22], and Posey [23].

THE EASIGAMI SYSTEM

We describe the hardware and software components in this section, and in the following section we outline a few applications that we have built.

The Easigami system consists of a tangible user interface and a software application. The TUI is a set of polygons connected by detachable hinges instrumented to sense their angles, and a local microcontroller to manage the hinges. Software running on a PC assembles, maintains, and displays a model of the physical TUI, making that model available for applications.

The Easigami TUI

Alone each polygon is static, an uninstrumented flat panel. However, when connected with sensing hinges it becomes part of the TUI. Shapes are coded with different colors, helping the user to match the TUI in hand with the graphical object on the screen.

The polygon pieces (see Figure 2) include equilateral, isosceles right triangles, squares, pentagons, and hexagons. Two holes on each edge allow a polygon to attach to a hinge. All the polygons have equal length edges except for the isosceles right triangles, whose legs are the same length. Because of this any two polygons can be conveniently connected, which facilitates assembling a TUI. A wide and interesting range of polyhedral forms may be created from these polygonal building blocks.



Figure 2: Polygon Pieces: hinges attach through the holes.

Each hinge (see Figure 3) has two wings, each with a pair of circular Velcro pads that fasten through matching holes in the polygon side. Each wing is a sandwich of fabric with a cardboard core. The cardboard ensures that each polygon rigidly attaches to the hinge and remains so during manipulation. The fabric is sturdy enough to withstand repeated attaching and detaching of the Velcro snaps. Like common origami paper, one side is white, and the other is a bright color to visually differentiate mountain and valley folds. We use both indices and eight different bright colors to mark the different hinges.

The detachable hinge has two electronic components: a rotary potentiometer and a bi-color LED (Figure 3). The potentiometer senses the dihedral angle between the two adjacent pieces it connects. A brass bar is used to rotate the shaft of the potentiometer. A bi-color LED can show if a hinge has been chosen for the current TUI and indicate to which direction it folds: red indicates a valley fold and green a mountain fold. Currently, all eight detachable hinges communicate their states to an Arduino Nano [24], which in turn conveys this information to a local PC running the Easigami software over a wired serial connection.

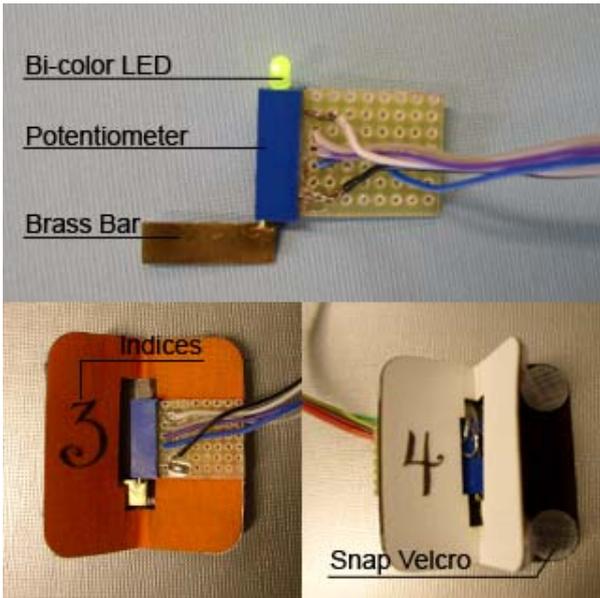


Figure 3: Hinges (Top: Embedded sensors; Bottom Left: Color coded side; Bottom Right: Reverse side is white.)

Software

Easigami’s software consists of two main parts: the 2D Pattern Builder and the 3D Form Explorer.

The Easigami 2D Pattern Builder (Figure 4) is used in the setup stage to register the physical components with the software’s internal model. The user chooses shapes from the palette of polygons and places them in the work area. When the user selects and joins two polygons, the program automatically generates a hinge notation with a unique ID number that specifies a particular hardware component. It displays the hinge color along the joined edge to indicate how the user should connect physical pieces using the matching detachable hinges. The user is responsible for ensuring that the physical configuration of the Easigami TUI matches the 2D configuration displayed on the PC. The topology information is then passed to the Easigami 3D Form Explorer. Figure 4 shows the net of a truncated tetrahedron under construction. Figure 1 shows the finished 2D pattern, the corresponding Easigami TUI, and the 3D digital model that it communicates with.

The Easigami 3D Form Explorer is synchronized with the physical input device that reports the angles sensed by each potentiometer. Based on the 2D pattern and hinge angle data, a real-time 3D digital form is displayed on the screen along with the corresponding 2D crease pattern. The user interacts with the digital model by manipulating the Easigami TUI.

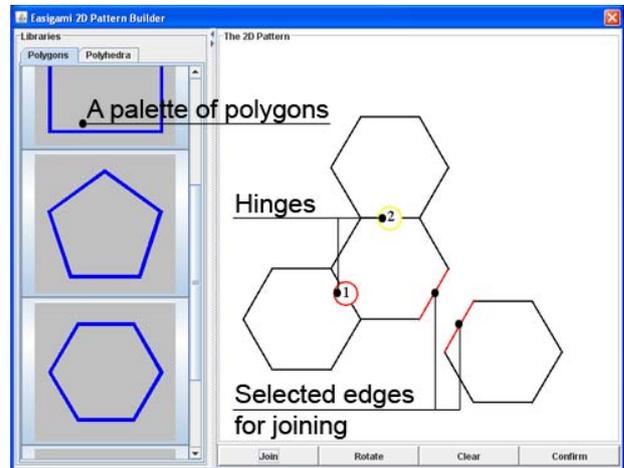


Figure 4: The Easigami 2D Pattern Builder

Accurately simulating the folding behavior of real paper is difficult because paper can be continuously curved and flexed. We avoid this problem by displaying a mesh that corresponds exactly to the physical polygon toy. The polygons are rigid planes and cannot be flexed; our graphic display also obeys this constraint. Generating an accurate picture of the physical toy at any time is relatively easy because we need only to draw each polygon in its correct position and orientation, which we can determine from the hinge angles. The primary data structure of a 3D model is a list of polygons with a list of hinges. A folding movement is simulated using the matrices of 3D rotation about an arbitrary axis, which is always a line segment of the 2D crease pattern.

APPLICATIONS

In traditional origami the “game is over” when a folded model has been achieved. Children are not typically encouraged to unfold a model to observe the relationship between the 3D model and its 2D crease pattern. Unlike traditional origami, which starts from a plain square paper, the design of the Easigami tangible user interface emphasizes the underlying structure – the folding pattern, as it is an abstraction and a reduction of a folded model [25].

Most origami instructions guide the maker through a specific paper model: the frog, the crane, the fortune-teller and so on. They teach the art of paper folding by rote learning rather than encouraging children to invent new models. Children can reproduce models as taught but seldom explore inventing new models. In contrast, Easigami is designed to encourage users to create new folded models.

Mathewson [26] proposed several categories for early learning of visualization to go along with current concentrations on 'literacy' and 'numeracy', including Visual-Spatial Exercises, Active (hands-on) Learning, and Visual Analogy. We designed the Easigami system with an eye to all three of these categories.

We have implemented prototype applications for the Easigami system whose goal is to provide new experiences for children to explore geometry – specifically, polyhedra and 2D-3D transformations. The applications are intended to enhance and augment young people's visual and spatial abilities.

The Game of Nets

Similar to origami's 2D crease patterns, we can see the net of an unfolded polyhedron, also known as a development, pattern, or planar net. Some solids have multiple candidate planar nets. The goal of the Game of Nets is to build children's spatial intuition by showing them the folding and unfolding of nets/meshes into polyhedra. It also provides training for children to learn to use the Easigami TUI with the software.

The object of the Game of Nets is to recognize which among a set of planar nets matches a given polyhedron. One game variant requires selecting the correct net among a set; another variant requires finding which is the incorrect net among a set of candidates. A reversed game design displays the net and then asks which solid(s) could be constructed by the given pattern. In all these game designs, children can build the Easigami TUI for the polyhedron, and then fold and unfold it to solve the challenge.

Building a Polyhedron

We provide a library of 3D models of polyhedra such as Platonic solids and Archimedean solids that can be achieved using the detachable hinges and the set of 2D polygon kits. Children usually are taught about these polyhedra by being told some facts, such as: "A cube has 6 surfaces, 8 vertices and 12 edges". In contrast, Easigami is a toy for children to explore the properties of a polyhedron without first knowing these factual assertions. Rather, children can discover these facts themselves through physical and tangible manipulation.

For example:

- The child creates a polyhedron that has not been taught. It may be a polyhedron that is not in the current library, or even a new type of polyhedron as the definition of polyhedron is vague.
- The net constructed could not achieve a polyhedron so that the child must add, remove or replace some polygons or modify the initial configuration. In this case, we imagine an extended version of Easigami in which the system provides suggestions based on the nets stored in an existing (and extendable) library.
- There might be more than one solid that a net can produce. For example, a boat and an octahedron share the

same pattern [27]. When one is completed, the system will point out the other possibility.

Playing with Folding Free Forms

In addition to polyhedra, children can construct a 2D pattern such as a belt or a sheet. Figures 5a and 5b show two Easigami TUIs – both use eight pieces of isosceles right triangles. They are crease patterns of two simple origami base folds: Blintz Base and Balloon Base. Figure 5 also shows when a user plays with the triangle mesh of a Balloon Base, a variety of 3D forms can be generated from the 3D Form Explorer.

We see the potential that from the same set of the polygons, there are other alternative ways to construct the folded-sheet TUIs, each of which would produce a diversity of 3D forms during an interaction process.

DISCUSSION AND FUTURE WORK

We are interested in how computational media can be integrated with traditional craft and construction. Traditional crafts remind us of what we might miss when we interact with most computer interfaces. Traditional origami presents us a method with which, using simple material we can build a diverse universe. As we tried to augment this classical craft technology digitally, we began to respect it more. We have taken a "low-tech" approach to our design, opting for simpler and less expensive solutions over more sophisticated technical ones. Less is more.

To maintain the look and feel of paper, we use thin materials for the physical polygon elements. This involved experimenting with different materials including conductive fabric and different types of cardboard. Meanwhile, even a simple hinge design requires a series of modifications. For example, magnetic snaps function like Velcro for fastening but they restrict rotation angles because of their thickness. We considered including tilt sensors so that the computer can sense the orientation of the Easigami TUI. We decided not to add more sensors or micro-controllers to the polygon TUI so that the planar polygon elements would not have a thick or bulky edge. We focus on developing thin pieces and adopt miniature rotary sensors. We try to mimic a piece of paper used in origami folding.

Even though we could instrument the Easigami TUI to sense the configuration of the polygons and automatically update the display whenever a new polygon is added to the TUI (as for example illustrated by the Triangles project [28]) we decided not to do this. Although technologically more sophisticated, this approach of instrumented polygons also makes it harder for a user to expand their own shape set.

Currently, the polygon pieces are laser cut from cardboard. A user can easily draw new polygon shapes, cut them and add them to the current polygon set to extend their shape universe. Another consideration is cost – we prefer design strategies that lower cost as they will be accessible to more potential users.

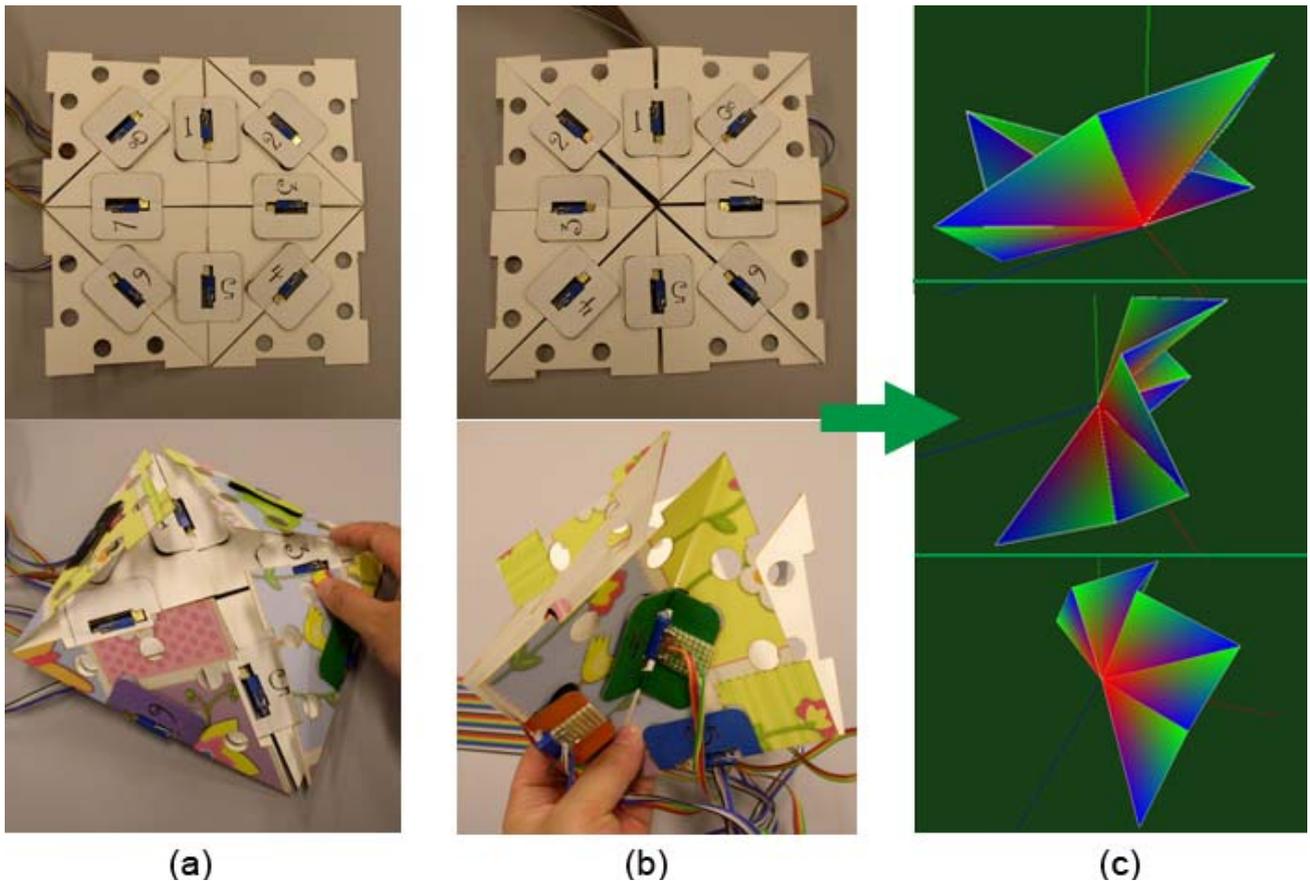


Figure 5: Folding Free Forms – (a) A TUI with the Blintz Base; (b) A TUI with the Balloon Base; (c) 3D digital models generated by the TUI in (b).

Interesting problems arise in the design process. For example, choosing an input device for a specific task could be challenging – in the current Easigami system, we still use the mouse to create the graphical counterparts of the TUI in the simulation display. This makes Easigami a hybrid of both tangible and graphical user interface. The question remains: what should the design decision be for a TUI-GUI hybrid system? Should we replace or augment the mouse and keyboard interface with another input device? Shall we employ a TUI for all the interactions needed in this type of system?

Careful engineering and integration of software and hardware design is needed in developing a system like Easigami. It is not obvious which interaction should be physical and which should be digital. For the physical design, the material and geometric form affect the function as much as the electronics design. Designing a tangible interface is an iterative and incremental process. At times the physical form dictates the choice of specific electronic components and the resulting algorithms used in the digital simulations. Sometimes the software design calls for a particular sensing platform to supply the necessary inputs.

In previous work, researchers have built software prototypes of intelligent paper that recognizes hand drawn sketched diagrams [29], and uses this recognition to

provide various kinds of feedback. Easigami extends this idea of intelligent paper to provide feedback of the physical world through three-dimensional modeling and simulations of the folding actions.

Currently the Easigami system is fun to play with but it is also cumbersome: the wires that connect each hinge to the microcontroller limit the flexibility of folding. Future work will focus on improving the usability of the hardware. We would also like to experiment with different material and physical design of the hinges to support more flexible folding.

We would like to encourage children to invent and self-define new shapes. Once an interesting new model is created, it can be added to a library for later use. Children can then share their new models with others, to discuss and engage in more creative geometry explorations.

SUMMARY

Easigami employs the mechanism of construction kits and performs as a toy-like input device to engage children in a visual-spatial folding activity. Children have more fun when they use their hands to explore new models. It makes learning more like a game and makes interaction more intuitive. Easigami exemplifies an interactive environment where physical and digital worlds are integrated to assist users in a creative spatial task.

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