AutoGami: A Low-cost Rapid Prototyping Toolkit for Automated Movable Paper Craft

Kening Zhu[1,2,3], Shengdong Zhao[1,2]
[1]NUS-HCI Lab, [2]NGS, [3]Keio-NUS CUTE Center
National University of Singapore, Singapore
zhukening@nus.edu.sg, zhaosd@comp.nus.edu.sg

ABSTRACT

AutoGami is a toolkit for designing automated movable paper craft using the technology of selective inductive power transmission. AutoGami has hardware and software components that allow users to design and implement automated movable paper craft without any prerequisite knowledge of electronics; it also supports rapid prototyping. Apart from developing the toolkit, we have analyzed the design space of movable paper craft and developed a taxonomy to facilitate the design of automated paper craft. AutoGami made consistently strong showings in design workshops, confirming its viability in supporting engagement and creativity as well as its usability in storytelling through paper craft. Additional highlights include rapid prototyping of product design as well as interaction design such as human-robot interactions.

Author Keywords

Automated paper craft, paper computing, toolkit, selective inductive power transmission.

ACM Classification Keywords

H.5.2. User Interfaces: Interaction styles, Prototyping

INTRODUCTION

In 1998, Wrensch and Eisenberg embedded computation in arrays of low-cost material substrates available to crafters to enable enhancement of our daily lives through the easy and economic design of intelligent everyday objects [28]. Among low-cost materials, paper stands out because of its unique advantages: it is easy to use, flexible, lightweight, and readily available. As a traditional medium for art and communication, it has long been popular for creating 2D and 3D models as well as paper craft.

To embed computation and interactivity in paper crafts, researchers have explored the use of shape-memory alloy (SMA) [8] in triggering the movements of paper electrically. This lightweight, flexible metal alloy can be directly integrated with paper, which makes it a preferred material in movable paper craft [16]. Using SMA, it is possible to incorporate mechanisms such as flaps, pull tabs, and volvelles (rotary wheels) that cause movement on the 2D paper surface or above the surface in 3D space [25].

In the past few years, a number of studies have focused on generating and enhancing paper movements using digital technology [6, 9, 10, 13, 14, 17, 20]. This body of research ranges from simple movement to relatively complex shape-changing using microelectromechanical systems (MEMS), which significantly advanced the technology for movable paper craft. Current research development for movable paper craft can benefit from the systematization of existing research results and the creation of a unified body of engineering and design knowledge.

We analyzed the design of movable paper craft and developed a taxonomy that focuses on the movements of single and multiple pieces of paper; subsequently, we generated a pattern language for automated movable paper craft.

More importantly, we developed AutoGami, a toolkit that allows users with no prior knowledge of electronics to design automated paper craft by using the taxonomy as a guide. AutoGami's software interface allows users to plan a variety of paper craft movements: its use of selective inductive power transmission [29] allows users to control aspects of movement such as duration, amplitude, and sequence without concerning themselves with technical implementation. Compared with previous work on automated paper craft (Table 1 and Table 2), AutoGami provides additional controllability and customizability.

This paper provides the following contributions.

- A systematic analysis of the design space for automated movable paper craft.
- A low-cost rapid prototyping toolkit for automated movable paper craft using the technology of selective inductive power transmission.

Usage Scenario

To highlight the main features of AutoGami and to demonstrate how the toolkit can help enrich people's daily lives and improve their efficiency at work, we first describe three usage scenarios. These scenarios are carefully selected based on the feedback and observation of over 400 people from demonstrating AutoGami on many occasions, including five workshops (described in more details in the evaluation section), a two-day local Maker Faire, a three-day interior design exhibition, a one-day open house exhibition, and two peer laboratory visits.

Storytelling Using Automated Paper Craft

Jean is a housewife and mother of a five-year-old boy, Tom, and a three-year-old girl, Kate. Just like most kids, both Tom and Kate love to hear stories from their mother. But because they are very young, some of the concepts in the story are difficult for them to grasp. Jean wants to enrich the stories with visual animation. Inspired by the traditional Chinese shadow puppet, she decides to create an animated paper puppet theater and invests in the AutoGami toolkit. She animates the story of The Hare and The Tortoise by first making the characters on paper (Figure 1) then using AutoGami's software and hardware to design simple movements.

Figure 1: Movable paper characters for telling the story, The Hare and The Tortoise using AutoGami

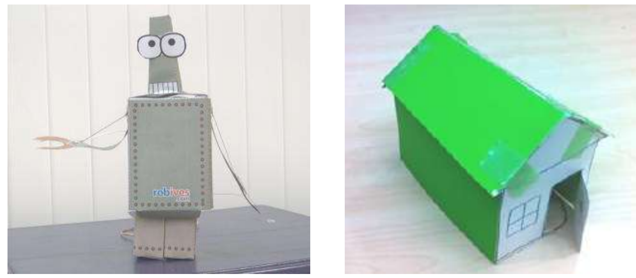
While she tells the story, she makes the paper characters move accordingly: Hare moves fast in the beginning but slows down after a while. Tortoise, on the other hand, moves slowly but consistently. As time passes, Tortoise surpasses Hare and wins the race. Both Tom and Kate are engaged in the story, cheering for the Tortoise as it moves, and clapped when it wins. Because of AutoGami, Jean can tell stories in a much more vivid way. And since it is simple and easy to use, telling animated stories can be a daily activity that is enjoyed by all members of the family.

Rapid Prototyping in Intelligent Devices

John is a researcher specializing in social robotics and intelligent environments. In his next project, he will be creating social robots that have different personalities and look and feel. The movements he needs to design range from saying greetings, nodding and shaking the heads, and facial expressions.

John needs to test different types of movement so that he can assign the appropriate one for each robot. After making the paper models for each robot, as shown in Figure 2(a), he uses AutoGami to design movements, test their various types, and study each one's different patterns by adjusting parameters such as the duration and the range of movement. AutoGami's rapid prototyping system made it possible for John to identify specific types of movement appropriate for each robot, which in turn allowed him to determine the most suitable hardware to support each type of movement. He was able to save both time and money because the toolkit was easy to use, he was able to create prototypes using accessible material, and he was able to conduct tests before purchasing the necessary hardware.

John also uses AutoGami to simulate smart home behaviors. He builds a 3D paper model of a house (Figure 2(b)). Using AutoGami software, he designs the movement of the door and the window. John found the automated paper craft prototypes a very useful and effective means for both previewing the intelligent behavior and to communicating the idea with his colleagues.



(a) **(b)**

Figure 2: (a) Robot prototyping using AutoGami; (b) Smart home prototyping using AutoGami

Interactive Art Design

Mary, a paper craft artist, was invited to exhibit her work in the city museum. To make her artwork more engaging, the museum suggested using digital technology. Mary, who has limited knowledge in technology, uses AutoGami to automate her paper craft. After trying out the toolkit for the first time, she finds that it can trigger movements in different origami without the need to connect them to complex circuits. She creates different origami, such as a crane with flapping wings and a dog with a moving mouth. She also creates an array of origami flowers that she will arrange to depict pixels in a matrix display. She designs movements so that groups of flowers bloom at different intervals, creating different patterns that display in a sequence.

AutoGami made the design process efficient because Mary could arrange and rearrange the position of the flowers and test the different parameters for blooming. Automating paper craft was easy and fast because Mary only needed to attach actuators to the origami and plan the sequence of blooming in the GUI. At the exhibition, the automated artwork was well-received by the audience, who were amazed by how the paper craft was animated without the use of electronic wires.

The above scenarios illustrate the capabilities and potential of our toolkit. We now discuss the background and related work that motivate us to create AutoGami.

BACKGROUND AND RELATED WORK

Throughout the evolution of paper, artists and designers have created various art forms through techniques such as folding, bending, and pop-up [22]. Today, paper craft is used in many other areas, such as storytelling, education, and medical treatment. Making paper craft has shown to improve children's creativity, spatial reasoning skills, and performing ability [21]. Paper craft can also be used to enhance in-class communication among teachers and children, and to help develop cognitive and language abilities necessary for reading and writing [7, 15]. However, while traditional paper craft have played an essential role in enriching art and culture, they are generally static; at most, they allow only manual or mechanical interaction, limiting their potential in the digital age.

Our work was inspired by various efforts toward the integration of the physical and virtual worlds, including tangible and physical computing [11], augmented reality environments [27], ubiquitous computing [26], and the emerging digital art-related research in the CHI community (i.e., [18, 19]). It is a contribution to the research on automated movable paper craft using SMA and to toolkits for creating movable craft.

Automated paper craft using SMA has drawn interest from researchers since the late 1990s and early 2000s. The first project that used SMA in paper craft we aware of was the Programmable Hinge [28], wherein SMA was attached to a paper-made hinge structure and controlled by an external microcontroller. The Programmable Hinge set an early example of implementing automated movable paper craft for the following projects. In the Interactive Paper Devices project [20], Greg Saul et al. introduced a method of embedding electrical circuits with sensors and actuators using conductive gold leaf gilding. They also presented paper prototypes of a robot, speakers, and LED lamps.

Coelho et al. [6] improved on the method of embedding electrical circuits by developing pulp-based computing, a set of techniques for building sensors, actuators, and circuit boards that behave, look, and feel like paper. Jie Qi et al. [17] created Electronic Popables, an interactive pop-up book that integrates electronics and pop-up mechanisms as a unified story book. Animated Paper [14] is a hardware platform created from paper and shape memory alloy (SMA), which is easy to control using different energy sources ranging from sunlight to lasers. Paper craft is actuated by SMA and its movements controlled with a high-power laser pointer.

In 2012, Jie Qi et al. [16] presented a set of mechanisms for actuating paper with SMAs that produced, among other things, the folding flap, parallelogram, curling flap, and clam shell, and tested one of these mechanisms in workshops. A few projects on automated paper craft used motors (Oribotics [9], Adaptive Blooming [13]) and MEMS (Programmable Matter [10]) instead of SMAs. However, SMA has the advantage of being low-cost, lightweight, and easily integrated with paper.

Leah Buechley et al. [3] used the extended LilyPad Arduino to introduce one of the first paper computing kits, which could be attached to the book page by magnetic snaps. It needs circuit planning for creating paper books that produce light and sound. Designing the output circuit also requires users to have prerequisite knowledge and experience in electronics. In addition, the complex circuitry and massive wiring increases the bulkiness of paper.

We developed our toolkit based on the technology of selective inductive power transmission [29]. Compared with the movable craft toolkits we described previously, ours doesn't require users to consider the design of the circuit and wire connection. They only need to attach the power receiver with actuator to the paper to implement their design. In addition, AutoGami has a software interface that allows users to plan and preview the movements before implementing them on paper.

ANALYSIS OF MOVABLE PAPER CRAFT

To understand the capability and limitation of prior work in movable paper craft, we conducted a detailed analysis, including the literature on traditional movable paper craft [12, 23, 24] and nine papers on automated movable paper craft that have been published in the past ten years [6, 9, 10, 13, 14, 16, 17, 20, 28]. Based on the analysis, we developed a simple taxonomy to classify the types of movement supported by existing movable paper crafts (Figure 3) and a pattern language to formally analyze and compare the existing systems.

Taxonomy of Paper Movement

Taking our cue from the motion-centric taxonomy for classifying human manipulation behavior created by Bullock et al. [4], which divides hand motion into *Within Hand* and *Not Within Hand*, we classified the movements of paper craft in two main categories: *Single Paper*, which consists of movements created by one piece of paper, and *Multiple Paper*, which consists of movements created by multiple pieces of paper (Figure 3).

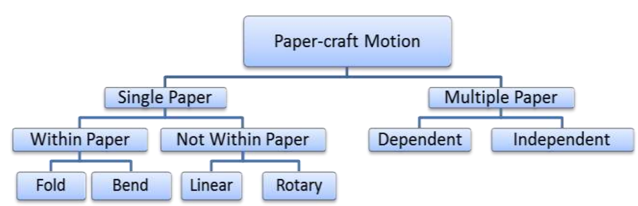
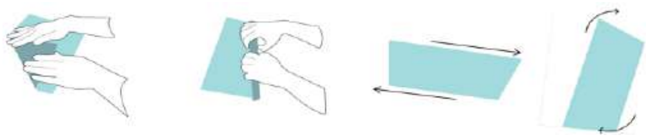


Figure 3: Classification of paper movement

Single Paper has two subcategories, which are defined by where the movement occurs:

Within Paper - Movement that occurs in parts of the paper, such as folding or bending paper (Figure 4) to further classify the more complicated movements of paper craft under subcategories of *Within Paper* and *Not Within Paper*.



(a) (b) (c) (d)

Figure 4: Movement primitives of single piece of paper: (a) fold, (b) bend, (c) linear translation, (d) rotation

Fold - creates a crease; a combination of creases creates origami. Fold refers to folding in one direction and multiple directions (Figure 4(a)).

Bend - changes the paper's shape without creating creases; because of its texture, the paper usually reverts to its original shape after the bend is released. Bend includes bending forward and backward (Figure 4(b)).

Linear - movement in 1D, 2D, and 3D space (Figure 4(c)).

Rotation refers to the orientation of the paper craft. Movement along the axis can occur in 2D and 3D space (Figure 4d).

Multiple Papers also has two subcategories:

Dependent - The movement of one paper could trigger the movement of another paper. This type of movement is common in movable paper craft [12], which uses traditional mechanical structures such as gears and pulling bars. In movable paper craft, we can equate dependent movement in terms of input-output relationship.

Independent - The movements of multiple papers have no cause and effect relationship. Each paper's movement is triggered by different sources.

Pattern Language for Automated Paper Craft

The taxonomy of paper movement describes one important dimension a movable paper craft system can support. To comprehensively classify a system, a more systematic description is needed. Thus, we designed a pattern language as inspired by Card et al. [5].

In our pattern language, an automated movable paper craft can be abstracted into a four-dimension vector:

(Movement, MovementStyle, R, W)

Where: *Movement* is the possible movements generated in the paper craft. It includes all the movement primitives mentioned above in the subcategories of *Within Paper* and *Not Within Paper*.

MovementStyle is either *continuous* (perpetually moving) or *binary* (moving or not moving).

R is the dependency between different movements.

W is a set of general rules that describes the properties of the paper craft, how the system works, and its constraints.

Our pattern language uses the following set of operators:

$$< \&, |, \rightarrow, \neg >$$

Where: & (*and*) means the output movements can be performed at the same time. For instance, a paper craft can be folded and perform linear movement on a surface at the same time with any system-mode changing, such as button pressing.

| (*or*) means the system can only process a single output at a time, which would lead the mode-changing of the system.

→ (*dependent*) shows the connection between input and output, where the starting point is the input method, and the end point is the output result.

¬ (*binary*) means the movement is performed in continuous or binary style.

We then used this pattern language to analyze four existing automated paper crafts as examples.

The *Programmable Hinge* [28] can control the rotation angle of the hinge through a microcontroller. Using the pattern language, we can describe it as:

ProgrammableHinge = (Movement: 2DRotary, MovementStyle: Continuous, R: {}, W: {})

In *Animated Paper* [14], SMA animates paper craft by bending, which causes it to move on a flat surface:

AnimatedPaper = (Movement: Bend, Linear, MovementStyle: Binary, R : ¬Bend → ¬1DLinear|¬2DLinear, W: {})

In *Animating Paper with SMA* [16], there is multiple bending and folding. Since they cannot be performed at the same time, the movements have an | (or) relationship:

AnimatingPaperWithSMA = (Movement: Fold, Bend, MovementStyle: Binary, R: ¬Fold|¬Bend, W: {})

In *Interactive Paper Devices* [20], the movement of the paper robot was triggered by bending the SMA.

InteractivePaperDevices = (Movement: Bend, MovementStyle: Binary, R: ¬Bend, W : {})

Table 1 shows the analysis of these examples and other related work in automated movable paper craft, including the use of SMAs, motors, and MEMS as movement actuators. The dashed line indicates the | (*or*) relationship between two movements.

The taxonomy and pattern language helped us understand the capabilities of the prior work and allowed us to identify a number of areas for improvement. First, we find the number of movement types supported by previous systems cover different and often limited number of cells in Table 1. Most of them only support binary movement (i.e., [6, 14, 16, 17, 20]). In Animating Paper with SMA, for instance, movement is still relatively unsophisticated: it is controlled by switching the power supply on and off. A power on/off

①: Programmable Hinge [28]
②: Interactive Paper Devices [20]
③: Animated Paper [14]
④: Electronic Popables [17]
⑤: Animating Paper with SMA [16]
⑥: Pulp-based Computing [6]
⑦: Oribotics [9]
⑧: Adaptive Bloom [13]
⑨: Programmable matter by folding [10]
⑩: AutoGami

Not Within Paper					Within Paper				
Rotary Motion		Linear Motion			Bend		Fold		
2D	3D	1D	2D	3D	Single Direction	Multiple Directions	Single Direction	Multiple Directions	
		③	③		③ ⑤ ④		⑥ ⑤② ④		Binary
⑩			⑩		⑩	⑩	① ⑨ ⑩	⑦⑧ ⑨ ⑩	Continuous

Table 1: Comparison of related works using the taxonomy of paper movement. This table shows that AutoGami supports a large range of movements as compared with other alternative systems.

pattern is used, for example, to flap the wings of a paper crane.

Second, the support for designing movement is limited. Except for Interactive Paper Devices [20], others do not have a graphical user interface for designing movement.

Third, existing toolkits either support rapid prototyping without sufficient controllability and customizability (Programmable Hinge [28] and Animating Paper with SMA [16]) or require electronic knowledge on the part of users in order to create circuits for programming and controlling the movement of paper craft (Interactive Paper Devices [20]).

Fourth, some use expensive and proprietary technologies (i.e., Animated Paper uses a high-power laser for heating up the SMA), making them less accessible.

To overcome some of the above limitations and to make automated movable paper craft accessible to more users, we developed AutoGami.

AUTOGAMI: A TOOLKIT FOR CONSTRUCTING AUTOMATED MOVABLE PAPER CRAFT

AutoGami is a low-cost and easy to use toolkit that runs on selective inductive power transmission [29], which allows paper craft to make more types of movements, and fully explores the taxonomy of automated paper craft. Its graphical interface makes designing and programming easier as it requires little or no engineering knowledge, supports rapid trial-and-error testing via simulation. Compared with existing systems and toolkits, AutoGami can support more movement types, as specified using the pattern language below.

AutoGami = (Movement: Rotary, Linear, Fold, Bend,
MovementStyle: Continuous, R: Rotary|Linear|Fold|Bend, W: {})

Implementation

Figure 5 shows an overview of AutoGami toolkit. The AutoGami hardware is developed based on the technology of selective inductive power transmission, which consists of controllable power transmitter and power receivers. In addition, the hardware part is connected to the controlling software through Arduino interface.

Hardware

The transmitter has a push/pull MOSFET oscillator with high output power. The LC tank in the system generates the oscillation, and two power MOSFETs amplify it to enable the system to transfer more energy wirelessly. As shown in Figure 6, a one-turn antenna with a diameter of 100 mm is made of a 6-mm diameter copper loop. The power transmitter in AutoGami contains customizable slots that enable users to design their own wireless power transmitter by connecting different capacitors. In terms of controllability, the transmitter circuit could be connected to Arduino output through connection slots, or directly through the on-board switches, to turn the relays on or off and generate different output frequencies.

For the structure of the power receiver and movement actuator, we used LC tank to harvest energy at its resonance frequency. The inductor L in the system refers to coil made of 0.5mm enameled copper wire; it is circular with diameter of 5cm and has only 2 turns to match the small resistance of the SMA wire. The capacitor and the SMA are attached to 2 nodes of the copper coil. Each coil will have a different value capacitor attached, thus each will have different resonance frequency. For the movement actuator, we used spring-shaped SMA with the model of BMX100500 from TOKI Cooperation [1].

Software

AutoGami comes with software (Fig. 6) that facilitates the design of paper craft movements. Its GUI enables users without programming experience to draw the shape, and design the movements of the paper craft, assign actuators to the different movements, and set the sequence of those movements. The software allows the user to simulate movement using SMA before the automated paper craft is implemented in paper and SMA.

To automate paper craft with AutoGami, the user first creates the physical prototype of the movable paper craft, and then draws a model of it using the software, and designs movements by setting the amplitude and duration of different motions in the GUI. According to the IDs of the receivers, the user then attaches SMAs to different parts of

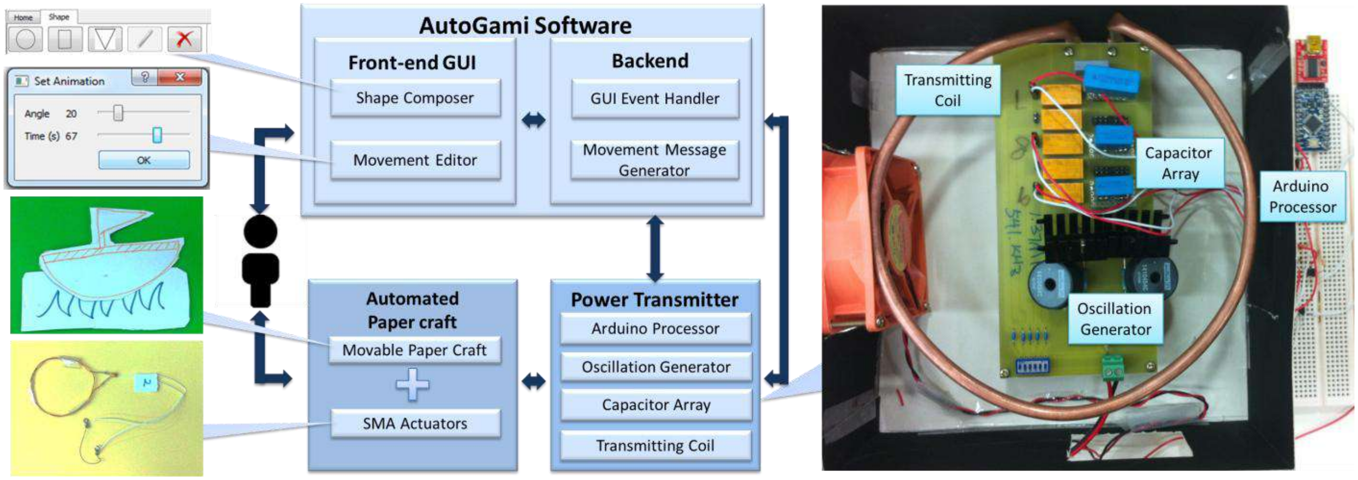


Figure 5: Overview of AutoGami's hardware and software

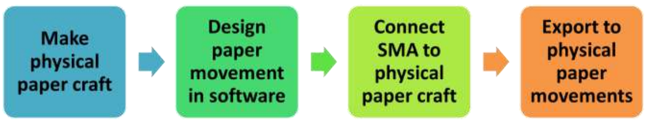


Figure 6: Steps of using AutoGami to create automated paper craft.

the paper craft, where movement will be triggered. When the power transmitter is on, the Arduino processor analyzes the information sent by the software and triggers a specific movement in the appropriate output frequency. Figure 6 is a step-by-step illustration of this process.

Features of AutoGami

AutoGami's software and hardware support features ranging from movement of different parts of a paper craft to creating a new type of movement using multiple actuators. We use a paper puppet of a bear (Figure 7(a)) to illustrate the toolkit's main features.

(a) (b) (c)

Figure 7: (a) A paper puppet made in AutoGami; (b) Replicating movements to another paper craft using the copy and paste method; (c) Final product of copy and paste

Moving different parts of the paper-craft separately

Selective inductive power transmission can activate different power receiving coils in different output frequencies. This allows users to assign a frequency to a movement that will be implemented in a particular part of the paper craft. The IDs of the joints in the drawing are mapped to power receivers with different resonant frequencies so that the user could identify the joint in the paper craft where he wants to trigger movement. In the case of the paper bear, the arm can be moved while the leg is static, and vice versa.

Adjusting the amplitude and the duration of different movements

AutoGami allows the user to set the amplitude, or range, of the movement, as well as how long the movement is performed. For example, the angle of a waving arm can be set to a certain degree, or a car can be set to move a certain distance. In Figure 5, slide bars are adjusted to set the amplitude and duration of a movement so that the paper bear waves hello by moving the arm at a small angle (20 degrees) for about 60 seconds, or waves goodbye by moving the arm at a wider angle.

Defining a sequence of movements

Users can define which movement is played before or after another movement. The sequence of movements can be arranged by setting the parameters of each movement (amplitude and duration) in a particular order. In the example of the paper bear, the user can set a sequence of movements so that the arm first waves goodbye then the legs move so that the bear walks away.

Replicating movement in another paper craft

Movements of one paper craft can be implemented in another through a physical copy-and-paste method. When two paper crafts have the same structure and are supposed to execute the same movements, the SMAs are simply attached to the same joints in the new paper craft. The sequence of movements that was created in the software

		AutoGami	Interactive Paper Devices [20]	Animated Paper [14]	Animating Paper with SMA [16]
Cost		~$100	~$200	>$1000	~$20
Knowledge Required		Paper craft making	Advanced electronics	Paper craft making	Soldering
Hardware Technology	Power Source	Inductive Power	Wire connection	Laser	Wire connection
	Hardware complexity	Low	High	Low	Medium
Controllability		Adjust the parameters of different motions	No	Binary on and off	No
Programmable		Yes	No	No	No
User interface	Paper craft Design	GUI	GUI	No	No
	Motion Design and Control	GUI	No	GUI	No

Table 2: Comparison of AutoGami and existing method for automating paper craft using SMA

interface is played to generate the same movements of the original paper craft. Figure 7(b) and Figure 7(c) show that the user only needs to set up the software once to make two or more paper bears execute the same movements.

Combining multiple actuators in one movement

The ability to selectively activate different SMAs allows the user to attach multiple SMAs to one movable part in the paper craft and set them up to move in different directions at the same time. This results in a new pattern of movement.

Comparison with Existing Toolkits on Paper Movement

We compared AutoGami with other toolkits in terms of expressiveness (customizability), cost, hardware interface, software interface, and prerequisite knowledge from users (see Table 2). With AutoGami, designing paper craft can be done at a lower cost, and knowledge in electronics is not required. There is higher controllability in designing movements, and the complexity of the hardware embedded in the paper craft is lesser.

Cost

AutoGami reduces the cost of hardware implementation by eliminating expensive processes and equipment such as gold leaf gilding and laser generators.

Prerequisite Knowledge from Users

AutoGami's design interface and attach-and-play method of implementation do not require advanced knowledge in electronics unlike Interactive Paper Devices, which require expert knowledge in circuit design and programming, and Animating Paper with SMA, which requires soldiering skills.

Hardware Technology

Interactive Paper Devices integrates an electronic circuit with a PIC controller into the paper material, which increases the complexity of the paper craft. Animating Paper with SMA also requires a copper-tape-based circuit to be embedded in the paper. On the other hand, AutoGami—like Animated Paper—uses attach-and-play, which merely requires the SMA to be attached to the paper to generate the movement.

AutoGami's use of inductive power has the advantage of eliminating massive wire connections to the external power source. Although Animated Paper also uses SMAs, it heats and powers up the SMA actuator with a high-power laser, an item that is not as readily procured and thus reduces the toolkit's accessibility.

Controllability and Programmability

The expressiveness of a toolkit refers to the extent it allows users to customize different movements, i.e., speed, time, sequence, and direction. Our experiment-based data shows that the speed of SMA contracting increases linearly with the current (in *Ampere* or *A*), as illustrated by the following mathematical equation:

$$Speed\ (cm/s) = 0.3218 * Current\ (A) + 0.0725$$

Animated Paper only allows binary control of the movement, which is triggered by switching the power on or off. Interactive Paper Devices and Animating Paper with SMA are more expressive than this, but AutoGami has higher controllability and programmability than these three toolkits because it can activate different actuators at different times.

Software and User Interface

Unlike other toolkits, AutoGami uses both GUI and physical interface in designing and controlling movements. This feature allows users to simulate the movements before implementing them to the paper craft.

WORKSHOP STUDIES

To evaluate the usefulness and usability of AutoGami, we conducted five workshops with an emphasis on the following questions:

How do users evaluate the intuitiveness and learnability of AutoGami?

Do users find the toolkit useful and engaging?

Is there evidence that the toolkit facilitates creativity?

We initially hoped to perform a comparison study with one of the three existing toolkits [14, 16, 20] listed in Table 1. However, Animated Paper [14] is a more costly, higher-end toolkit while Animating Paper with SMA [16] is simpler and less expressive than AutoGami. Thus, both are less than ideal for the purposes of comparison. Interactive Paper Device [20] is comparable to AutoGami in terms of cost and supported functionalities, but its software is not available for download and we don't have enough details to replicate the system.

Therefore, we have adopted the evaluation strategy followed by other creative systems, such as SandCanvas [18], and procedures used by Buechley et al. [2] for our evaluation.

Participants

Our workshops had a total 10 participants (2 people per workshop) consisting of five males and five females with ages ranging from 23 to 39 years (M=27.5, SD=4.81). The workshops were held in a meeting room with a dimension of 10 m x 7 m. Prior to conducting the workshops, we recorded the information on each participant's background skills in electronics and paper craft. Eighty percent of the participants considered their experience of electronics to be of intermediate level or lower, while 20% of them considered their background of paper craft to be of expert level but their experience in it to be at a lower level.

Apparatus

As shown in Figure 8, each participant worked with an AutoGami toolkit, which consisted of hardware (a transmitter connected to a power supply and two power receivers with SMAs in different resonant frequencies) and a software interface installed in a Lenovo ThinkPad X220. They were supplied with tools for making paper craft, such as paper, colored pens, scissors, needle, and wire. They were also provided with some premade paper crafts that they could examine and get inspiration from.

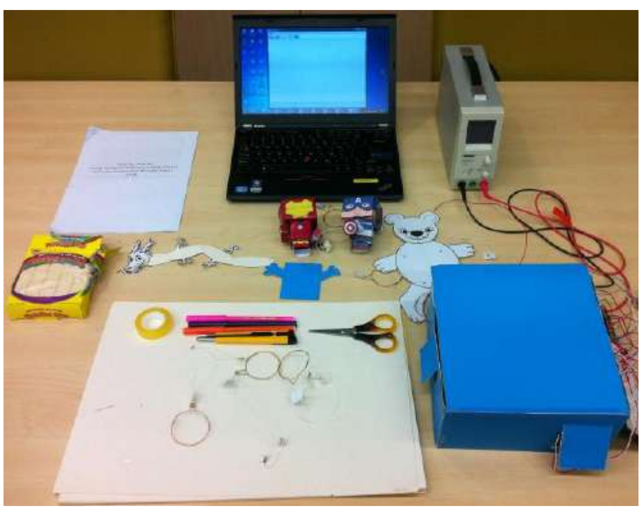


Figure 8: Setup of the workshop environment

Method

The workshop was conducted in four sessions:

1. Introduction. (*10 minutes*) The workshop facilitator gave a brief introduction of AutoGami and the technology of selective inductive power transmission, and showed a few examples of automated movable paper craft that can be made using AutoGami. The objective was to give the participants a brief understanding of the toolkit and the technology.

2. Guided Task. (*15–20 minutes*) After being introduced to AutoGami, the participants were given a printed tutorial on how to make an automated movable paper craft. The participants were asked to recreate this example to familiarize themselves with the AutoGami toolkit. The activity involved creating paper craft from scratch and planning the movements of two independent parts using the software interface.

3. Free Task. (*30–40 minutes*) Participants were grouped in pairs and were asked to explore their creativity and imagination by creating a new automated movable paper craft. This session aimed to provide us insights on how AutoGami allows users to explore their creativity.

4. Demo. (*10 minutes*) After making their own paper craft, each pair was asked to show a demo of the automated paper craft and explain the design rationale.

The workshop process was video recorded with the participants' consent. After the workshop, the participants answered a questionnaire on their impressions of the toolkit.

Results

User Evaluation of AutoGami's Intuitiveness and Learnability

Participants found AutoGami's hardware and software interfaces intuitive and easy to learn. One participant reported that it was *"easy to get used to the system"* and to working with the toolkit. Other participants commented: *"It is amazing to [familiarize myself] with a new technology and create an automated movable paper craft in less than one hour,"* that AutoGami can be easily and quickly understood, and that *"it is like the LEGO [of paper craft]."* The results of the questionnaire showed that intuitiveness earned a score of 4.5/5 while learnability scored 4.7/5.

All the participants were able to finish the guided task within the allotted time of 20 minutes. In the 40-minute free task, the participants were able to come up with different ideas for automated paper craft and implement them using AutoGami. They were allowed to ask questions when they faced difficulties, but very few did. There were, at most, two questions asked during each of the five workshops, which suggested that the toolkit was self-explanatory.

Nonetheless, the questions posed did help us to identify minor usability problems of the interface. Examples were *"Do I need to draw the exact shape of my paper craft? It seems I can only draw some simple shapes here,"* and *"What are the exact positions to attach the two ends of SMA?"* which indicate that the free-drawing function and the instructions on how to attach SMAs can be improved.

Figure 9: Automated paper craft created in AutoGami workshops

User Opinions on the Toolkit's Usefulness and Capacity to be Engaging

Workshop participants unanimously agreed that the toolkit is useful and that it can be employed in the following: teaching electronics, software, and interaction design to children; interactive storytelling; rapid prototyping for robot movements; designing smart furniture; and pure entertainment.

Overall enjoyment scored 4.5/5. It was observed that enjoyment increased when the participants were allowed to be creative. They were excited by the opportunity to create movable paper craft. This is reflected in the higher rating of enjoyment for the free task (4.7/5) as compared to the guided task (4.2/5).

Participants liked the toolkit, and most of them strongly agreed (4.4/5) that they wanted to recommend it to their friends. According to feedback, the toolkit is fun for introducing children to electronics, software, and movable paper craft; as one participant said, *"I had a great time playing with movable paper craft."*

Evidence of the Toolkit's Ability to Facilitate Creativity

Six pieces of automated paper craft were created during the five workshops, ranging from a natural scene to animals and from cartoon characters to architecture (Figure 9). A pair of girls used the copy-and-paste method to apply the same movements to a different paper craft. They used the same pulling movement on their cat's mouth and their elephant's nose. Another pair—an animation designer and an electronic engineer—adjusted the amplitude and duration of a movement to create a boat that moved in the waves. The boat's big movement depicted a bigger wave while a small movement depicted a smaller wave.

The post-workshop questionnaire also showed positive results in the area of facilitating creativity. The participants said that the toolkit allowed them to easily explore different possibilities of automatic movable paper craft, as evidenced by the score of 4/5 for this statement. Similarly, the statement "I became creative in automated movable paper craft using this toolkit" earned a score of 4.4/5.

In summary, the distributions of the scores for selected key questions are illustrated in Figure 10.

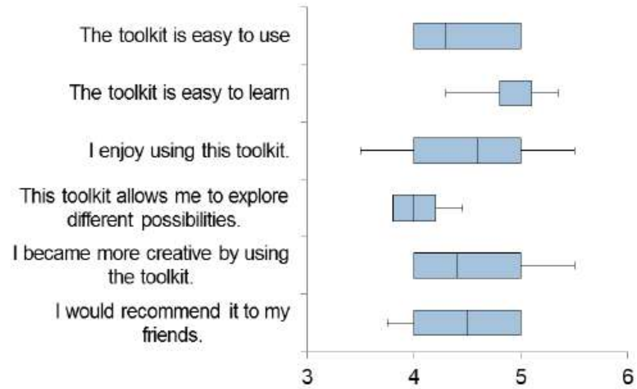


Figure 10: Score distribution for selected questions in the post-workshop questionnaire

Other Insights

Every group in the workshop used a similar process for designing automated paper craft. During the free task, most groups first decided on what real-world example to use for the automated paper craft. They then decided on the color of each part of the paper craft, as they identified color as an important characteristic. Finally, they decided on the movement the paper craft should make. This process motivated us to look at the properties of traditional paper craft—such as real-world examples, color, texture, and shape—in more detail as we improve the analysis of the design space on automated paper craft and further develop our toolkit.

LIMITATIONS

The current AutoGami hardware has limitations that prevent it from performing very complex, fast, and precise movements. AutoGami's software interface only supports drawing with simple shapes (e.g., circle, rectangle, and triangle). Thus, when using the GUI to draw a paper craft, the user can only draw its general shape. In addition, the size of the power-receiving coil needs to be optimized. It is relatively big compared to the size of the transmitter; as a result, it limits the number of receivers that can be placed on the inductive surface.

CONCLUSION AND FUTURE DIRECTIONS

In this paper, we have analyzed the research on movable paper craft by presenting a taxonomy and pattern language for this field. Our taxonomy can help researchers and designers to better understand previous work and to identify promising opportunities for new design. Motivated by our analysis, we developed AutoGami, a low-cost rapid prototyping toolkit for automated paper craft. Its software and hardware interfaces support the design of different patterns of automated movements in paper craft. The results of workshops have proven the usefulness of AutoGami, as users can create diverse, meaningful automated paper craft using the toolkit. Additionally, participants felt highly engaged in using AutoGami to create automated paper craft.

AutoGami provides a unique platform with rich capabilities, controllability, and expressiveness; it can also support various applications of automated paper craft such as storytelling, artwork design, and product prototyping. With further development of the toolkit, we aim to bring the joy of exploring and using automated paper craft to more users.

ACKNOWLEDGMENTS

We would like to thank Hideaki Nii for his guidance in designing and building the hardware prototype. We also thank members of the CUTE center and NUS-HCI lab for their generous help and support. This research is supported by the Singapore National Research Foundation under its International Research Centre @ Singapore Funding Initiative and administered by the IDM Programme Office.

REFERENCES

1. BioMetal, Toki cooperation. http://www.toki.co.jp/biometal/index.php.
2. Buechley, L., Eisenberg, M., Catchen, J., and Crockett, A. The lilypad arduino: using computational textiles to investigate engagement, aesthetics, and diversity in computer science education. In *Proc. of CHI 2008*, ACM Press (2008), 423–432.
3. Buechley, L., Hendrix, S., and Eisenberg, M. Paints, paper, and programs: first steps toward the computational sketchbook. In *Proc. of TEI 2009*, ACM Press (2009), 9–12.
4. Bullock, I., and Dollar, A. Classifying human manipulation behavior. In *Proc. of ICORR 2011*. 1- 6.
5. Card, S. K., Mackinlay, J. D., and Robertson, G. G. The design space of input devices. In *Proc. of CHI 1990*, ACM Press (1990), 117–124.
6. Coelho, M., Hall, L., Berzowska, J., and Maes, P. Pulp-based computing: a framework for building computers out of paper. In *Proc. of CHI 2009*, ACM Press (2009), 3527–3528.
7. Deborah, F, Origami and Communication Strategies. *Doshisha Studies in Language and Culture* 1-2, 315 – 334. 1998.
8. Falcioni, J. G. Shape Memory Alloys. *Mechanical Engineering*. April 1992, 114.
9. Gardiner, M., and Gardiner, R. The functional aesthetic of folding, self-similar interactions. In *Proc. of TEI 2012*, ACM Press (2012), 19-22.
10. Hawkes, E., An, B., Benbernou, N. M., Tanaka, H., Kim, S., Demaine, E. D., Rus, D., and Wood, R. J.., Programmable matter by folding, *In Proc. of NAS*, vol. 107, no. 28, 2010.
11. Ishii, H., and Ullmer, B. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proc. of CHI 1997*. ACM Press (1997), 234-241.
12. Ives, R., Ed. *Paper Engineering and Pop-ups FOR DUMMIES*. Wiley Publishing, 2009.
13. Justin Goodyre -- Constructing Realities | ARUP Phase 2 Gallery | London 2010. http://www.constructingrealities.com/?p=5.
14. Koizumi, N., Yasu, K., Liu, A., Sugimoto, M., and Inami, M. Animated paper: a moving prototyping platform. In *Adjunct Proc. of UIST 2010*, ACM Press (2012), 389–390.
15. McGee, L. M., Charlesworth, R., Books with movables: More than just novelties, *The Reading Teacher* 37 (9) 853-859.
16. Qi, J., and Buechley, L. Animating paper using shape memory alloys. In *Proc. of CHI 2012*, ACM Press (2012), 749–752.
17. Qi, J., and Buechley, L. Electronic popables: exploring paper-based computing through an interactive pop-up book. In *Proc. Of TEI 2010*, ACM Press (2010), 121–128.
18. Rubaiat, H. K, Chua, K. C., Zhao, S., Davis, R., Low, K.. SandCanvas: a multi-touch art medium inspired by sand animation. In *Proc. of CHI 2011*, ACM Press (2011), 1283-1292
19. Rubaiat, H. K, Igarashi, T., Zhao, S., Davis, R. Vignette: interactive texture design and manipulation with freeform gestures for pen-and-ink illustration. In *Proc. of CHI 2012*, ACM Press (2012), 1727-1736
20. Saul, G., Xu, C., and Gross, M. D. Interactive paper devices: end-user design and fabrication. In *Proc. of TEI 2010*, ACM Press (2010), 205–212.
21. Shumakov, K. and Shumakov, Y., Functional interhemispheric asymmetry of the brain in dynamics of bimanual activity in children 7-11 year old during origami training. PhD dissertation, Rostov State University, 2000.
22. Sloman, P., Ed. *Paper: Tear, Fold, Rip, Crease, Cut*. Black Dog Publishing, 2009.
23. Snyder, C., Ed. *Paper Prototyping: The Fast and Easy Way to Design and Refine User Interfaces*. Morgan Kaufmann, 2003.
24. Thelma R. Newman, Jay Hartley Newman, L. S. N., Ed. *Paper as Art and Craft: The complete book of the history and processes of the paper arts*. Crown Publishers, 1973.
25. Van S. D., Broman, E., E. G. K. R. A. M., Ed. *Paper Engineering: Fold, Pull, Pop and Turn*. Smithsonian Institution Libraries, 2010.
26. Weiser, M. The computer for the 21st century. *SIGMOBILE Mob. Comput. Commun*. Rev. 3, 3 (July 1999), 3-11.
27. Wellner, P. Interacting with Paper on the Digital Desk. In *Commun. ACM* 36(7): 86-96 (1993)
28. Wrensch, T. and Eisenberg, M. 1998. The programmable hinge: toward computationally enhanced crafts. In *Proc. of UIST* 1998. ACM Press (1998), 89-96.
29. Zhu, K., Nii, H., Fernando, O. N. N., and Cheok, A. D. Selective inductive powering system for paper computing. In *Proc. of ACE 2011*, ACM Press (2011), 59:1–59:7.