The Taxonomy, the Technologies, and the Toolkits for Technology-enhanced Movable Paper Craft

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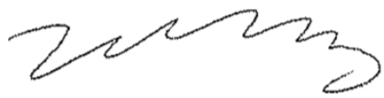
Declaration

I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.



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Summary

In the past decade, the concept of tangible user interface (OUI) has attracted much research interest into exploring new materials as human-computer interfaces that are naturally and intelligently dynamic during interaction. Paper, as a tradition medium for art and communication, shows great potential for tangible user interface with its intrinsic deformability and flexibility. Inspired by this fact, researchers have introduced the concept of paper computing, and various research works have been shown to utilize paper in human-computer interaction. However, a general taxonomy consisting of the design space and semantic model, and a facilitating toolkit, for designing paper-computing systems is still in need among this community.

This thesis presents the investigation of technology-enhanced movable paper craft. As defined, technology-enhanced movable paper craft (TEMPC) is a new type of paper craft with digital technology whose movements can be used as an input or output method for an interactive system. Existing research was studied and experimented to support the design and development of technology-enhanced movable paper craft. As the end products of this research, an analytic taxonomy was generated to abstract TEMPC into a mathematical model inspiring the development of new technologies for sensing paper-craft movement as input and generating movable paper-craft as output. Finally, a technical toolkit was developed based on the new technologies. User feedback during the toolkit workshops demonstrated that these end-products can facilitate the design of technology-enhanced movable paper craft.

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Chapter 1 Introduction

Humans have utilized paper in various applications such as writing, printing, packing, art, etc. *Paper Craft* describes artwork with paper material as the main carrier for artistic expression. While painting is only reflected by coloring on a 2D surface of paper, paper craft utilizes the special shaping of paper material in both 2D and 3D space to convey the artistic expression [95]. The emergence of multimedia publication is also pushing society to turn gradually into a paperless one, and paper material seems to be losing its value as the traditional culture carrier [13]. However, paper material still provides us novel possibility of creating artwork in the digital era. This sensitive, fragile, and soft material allows artists to explore their creativity fully. Besides art and decoration, paper craft is widely used in interaction design and prototyping [83]. The low cost and the easy accessibility of paper material allow designers to create low-fidelity and quick prototypes, such as sketching, paper cutting, paper folding, etc., and increase the efficiency of design iteration. The application of paper prototyping draws interest from researchers in using paper craft for human-computer interaction and expands the concept of Paper Computing [40]. Paper-craft-based interaction has been proven to enhance user experience with digital technology. However, being attached to computing technologies makes it harder for end-users to create their own interactive paper craft, and there is a lack of theoretical taxonomy and toolkits for guiding and creating interactive paper craft.

In this thesis, I define the term of technology-enhanced movable paper craft (TEMPC) as “the paper craft whose movement can be sensed and actuated as the input or output method for an interactive system.” This definition consists of two main elements: technology and movement. Technology is used to either sense or generate a set of movements of paper craft. As shown in Figure 1.1, my research aimed to tackle three main problems in the current developmental stage of TEMPC: diversity of movements, controllability of movements, and accessibility of tools. I first developed the taxonomy of TEMPC consisting of QOC design space and semantic language model, whose details will be presented in Chapter 3. The taxonomy serves as the theoretical foundation of this thesis, and it was used to further analyse the existing TEMPC systems and spot the possibility of improvement. Driven by the taxonomy analysis, I developed two TEMPC systems: origami recognition and origami generation. The study of these two systems provided important insights and lessons which led to the development a new technology for TEMPC, selective inductive power transmission, which reduces the technical complexity of TEMPC for end-users. The possibility of more controllability led to the development of Autogami, a toolkit for TEMPC. All these efforts and results built a road map to tackle the three main problems in current TEMPC research.

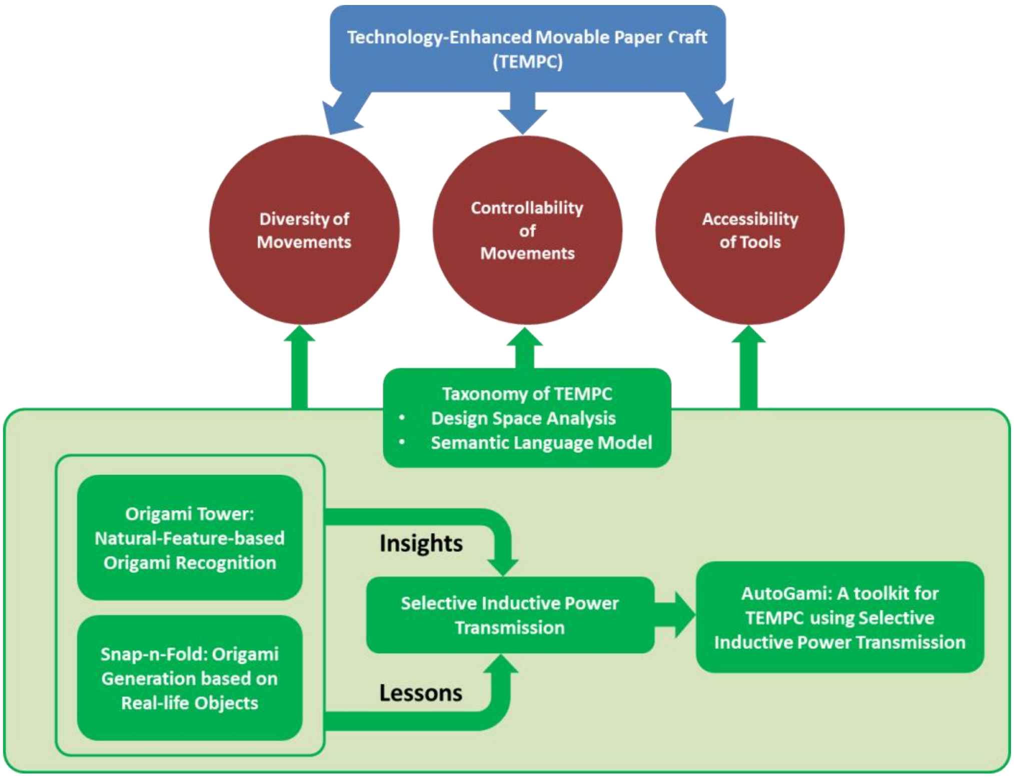

Figure 1.1: Overview of the thesis

The rest of the chapter provides an introduction on the history of paper craft, paper computing [40], and interactive paper craft, followed by the research questions which I aimed to answer with my research and the contribution of my research.

1.1 Background of Paper

Invented during the Han Dynasty in China, paper originated from the need to write, draw and document [82]. In addition, throughout the evolution of paper material, artists all over the world turned their attention to the material itself and created various forms of craft directly from paper, such as folding, cutting, and so on. In Japanese Shinto weddings, origami is used as a respectful symbolic practice to show the value of pureness [67]. Many Japanese samurais were keen to exchange their blades adorned by a special kind of paper flower as a sign of friendship [100]. Known as the inventors of paper, Chinese people have been using paper-cutting as a way of illustrating their folk tales and symbols to express good wishes, happiness, and love throughout the year [36]. The art of paper craft has also played an important role in western culture. In Switzerland, paper-cuts are not only used as decoration but also serve a more functional application to protect documents against forgery [82]. Silhouette, which uses only outlines and a featureless interior to illustrate a profile portrait, is another traditional art of paper-cutting in western society.

In contemporary society, besides cultural usage, paper craft has been used in many other areas, such as story-telling, education, medical treatment, etc. Origami occupies an interesting spot between mathematics, craft, and art. Shomakov's research shows that origami training affects brain development [80]. By playing origami, children can improve their creativity, spatial reasoning skills, and performance ability. In addition, origami can also be used to enhance in-class communication among teachers and children [17]. Origami is also used widely in both mental and physical therapy today.

Aberkrom conducted a testimony that showed the challenge of origami can free one from daily care and the anxiety of sickness [1]. Manual activities based on paper-cutting, such as paper pop-up, have been included in curriculum. McGee et al. [59] pointed out that pop-ups, when done cleverly, add not only to illustrations but to the enjoyment of the story, which could help children build bridges to more mature cognitive and language abilities necessary for tackling reading and writing. In HCI research, paper material has been widely used in rapid prototyping. Marc Retting [72] defined *paper prototyping* as "building prototypes on paper and testing them with real users;" this is also called low-fidelity prototyping or *lo-fi* for short. Compared to high-fidelity prototyping, paper prototyping allows designers to demonstrate the behavior of the interface in the very early stage of development and test with real users. It is fast, it is cheaper to make changes, and it allows a team to try far more ideas than they could with high-fidelity prototypes.

Although the rapid development of digital technology is gradually turning our society into a paperless one, research has shown that there are still rich advantages of using paper in daily life. Sellen and Harper [77] detailed the affordance of paper medium and its difference from digital medium in the office environment. They defined the word *affordance* as the fact that "the physical properties of an object make possible different functions for the person perceiving or using that object." The physical properties of paper material, such as thinness, lightweight, flexibility, opaqueness, porousness, etc., afford many different manipulations, like grasping, folding, writing, and so on. Their findings show that readers' needs, including flexible navigation, spatial lay-out of the information, annotating while reading, and interweaving, were better served by reading on paper than online. Sellen and Harper concluded that paper medium and digital medium do not totally overwhelm each other in terms of supporting knowledge work in the office. They pointed out the future possibilities and directions for designing new types of paper interaction and digital alternatives for paper medium. Mackay et al. [56] identified a few of the advantages of paper as a creative medium that are difficult to replace with standard computer interfaces: easy to use, lightweight, inexpensive, and ubiquitous, which is hard to attain in a realm of pure software. Motivated by the physical affordance of paper material, researchers started focusing on enhancing paper-based interaction using digital technology and have introduced the concept of Paper Computing [40].

1.2 Paper Computing & Technology-enhanced Movable Paper Craft

Inspired by the social and cultural value of paper, researchers developed the concept of Paper Computing [40], which appreciates paper as a good candidate for ubiquitous human-computer interaction. As defined [40], Paper Computing utilizes paper material as ubiquitous interfaces in everyday interaction with digital information. In fact, research in the field of human-computer interaction has attempted to address the need for interfaces to become more analogue in nature. First introduced by Mark Weiser [97], the concept of Ubiquitous Computing describes the idea of integrating computers seamlessly into everyday life. This idea then resulted in a rapid change in developing technologies whereby people live, work, and play in a seamless computer-supported environment. In 2006, the Future and Emerging Technologies (FET) unit in Europe planned and launched the research of Disappearing Computing. In this initiative, it is stated that the traditional computer will be replaced by a new generation of technologies which will make computing systems integrated into our everyday objects and environment and finally disappear into the background [78]. Last but not least, at PaperComp 2010 [40], the first International Workshop on Paper Computing, the participants claimed that far from a paperless world, paper could become ubiquitous interfaces in our everyday interaction with digital information. “This is the dawn of paper computing.” The initial motivation for the research of Paper Computing lies in facilitating digital document processing through traditional paper medium [40], including transferring digital content to paper document through computer-vision-based calibration and projection, and transferring paper document to digital format by recognizing the content in the paper document. In addition, paper as crafting material has attracted researchers’ interest. In the past few years, a number of studies have been performed on generating and enhancing paper craft using digital technology [14, 22, 25, 26, 29, 32, 37, 39, 43, 46, 49, 60, 61, 70, 71, 76, 79, 84, 91, 101].

In 1996, Robert J. Lang [46] first developed algorithms and software tools to automate the design process for origami. TreeMaker [47], by Lang, generates origami pattern based only on a designer’s drawing of the skeleton structure of the origami base. However, there is a lack of research effort following Lang in facilitating paper craft design until 2004. Jun Mitani et al. [60] developed an algorithm for designing origami architectures by using voxel data structure. It enables interactive design of origami architectures and easy generation of the unfolded pattern by making use of the characteristics of voxel representation and origami architecture. Susan Hendrix and Michael Eisenberg [32] developed Popup Workshop, the software to introduce children to the craft and engineering discipline of pop-up design in paper. In 2010, Xian-Ying Li et al. [49] developed an automatic algorithm, called Popup, for generating pop-up paper architectures given a user-specified 3D model. They have demonstrated this method on a number of architectural examples, with physical engineering results of paper pop-up.

Automatically sensing/actuating physical paper craft began attracting more attention in the late 1990s to present. As the first attempt of actuating physical paper craft, Wrensch and Eisenberg [101] created Programmable Hinge, which embedded computation directly in arrays of low-cost paper material and actuated automatic hinge movement. Marcelo Coelho et al. [14] invented Pulp-based Computing, which consists of a series of techniques for building sensors, actuators, and circuit boards that behave, look, and feel like paper by embedding electro-active inks, conductive threads, and smart materials directly into paper pulp. Inspired by Programmable Hinge and Pulp-based Computing, more and more researchers began exploring how to generate automated movable paper craft. Jie Qi et al [70] introduced shape-memory alloy into paper craft and created electronic pop-up books with switches, LED lights, and shape-memory alloy. Koizumi Naoya et al. [43] developed Animated Paper using high-power laser beams to control paper craft movement with shape-memory alloy. Kentaro Yasu et al. [102] utilized heat-shrink rubber to create paper pop-up movement. All these existing projects in enhancing paper craft with digital technology will be discussed in more detail in Chapter 2.

By summarizing the projects discussed above, I define this new type of paper craft: *technology-enhanced paper craft*.

In this thesis, the definition of *technology-enhanced paper craft* is derived from the existing effort in paper computing:

Technology-enhanced paper craft (TEPC) is a new type of paper craft with digital technology which can be used as an input or output method for an interactive system. Since there are various forms of traditional paper craft, technology-enhanced paper craft involves different enhanced properties, such as movements, colors, and shapes, etc. In this thesis, I mainly focus on my research contribution to technology-enhanced movable paper craft, which enhances the movements within traditional paper craft. Thus, I define technology-enhanced movable paper craft as:

Technology-enhanced movable paper craft (TEMPC) is a sub-category of technology-enhanced paper craft in which **movement** can be sensed and actuated as the input or output method for an interactive system. There are two main parts in technology-enhanced movable paper craft (shown in Figure 1.2): technology and paper craft movement that can be sensed or generated by the technology.

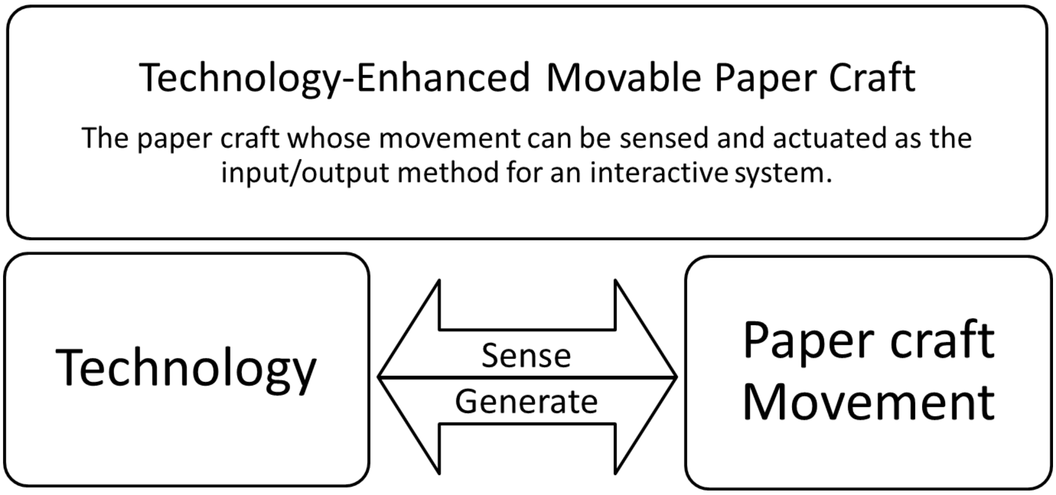

Figure 1.2: Definition of Technology-enhanced Movable Paper Craft (TEMPC)

By studying the existing research, I identified three important concerns in developing technology-enhanced movable paper craft:

- *Diversity of movement*

While paper craft has a large variety of movement, the existing projects have not shown a thorough coverage of the available set of movements. Jie Qi's workshop [70] is only about wing bending, although they list four different bending mechanisms. In Animated Paper [43], the paper craft can move in one direction with bending. There were few results showing whether these technologies or tools support users to explore the possibility of different movements, and there was no study done in analyzing the design space of technology-enhanced paper craft.

The problem of diversity of movement can be address by answering the question: *What are the taxonomy and the design space of technically-enhanced movable paper craft?* By definition [19], *taxonomy* means a method or scheme of classifying things or concepts, including the principles that underlie such classification. As defined in [87], the design space is, "A structured combination of design options having assigned a finite set of design options values that support the stakeholder's design decisions during the development life cycle of user interfaces." It should have all the design options and the design criterions for answering the questions arising during the design of technology-enhanced movable paper craft. It should be able to support the analysis and the comparison of existing design and inspire the new design of technology-enhanced movable paper craft.

- *Controllability of movement*

The existing method of technology-enhanced movable paper craft [14, 43, 70, 71, 76] only provides instruction on creating this type of paper craft with binary control, which means only a switch on/off of the technology is used to enhance the paper craft movements. This problem raised two research questions:

- What are the possible parameters in movable paper craft that can be controlled by technology?
- How does the technology control the movement?

- *Accessibility of design tools to end user*

In [70], researchers conducted workshops to teach participants how to use electronic tools before creating paper craft. The results of the workshop showed that users spent more time on learning how to use the electronic technology. Animated Paper [43] requires a high-power laser to activate the paper movement, but a high-power laser is expensive for most end-users. Therefore, there is no existing toolkit that is available to end-users in terms of usability and learnability. To tackle this problem, one needs to answer the following two questions:

- How should the technology support users to explore different types of movements?
- What is the nature of a general toolkit that is easy to learn and use?

1.3 Contribution

This thesis describes my investigation on these questions, including the study of the taxonomy of technically-enhanced paper craft, the development of TEMPC systems that provided insights and lessons on the design space, the new technology of selective inductive power transmission for TEMPC, and the toolkit for facilitating the design and development of technically-enhanced movable paper craft. These efforts finally lead to four main contributions of the thesis, as shown in Figure 1.3.

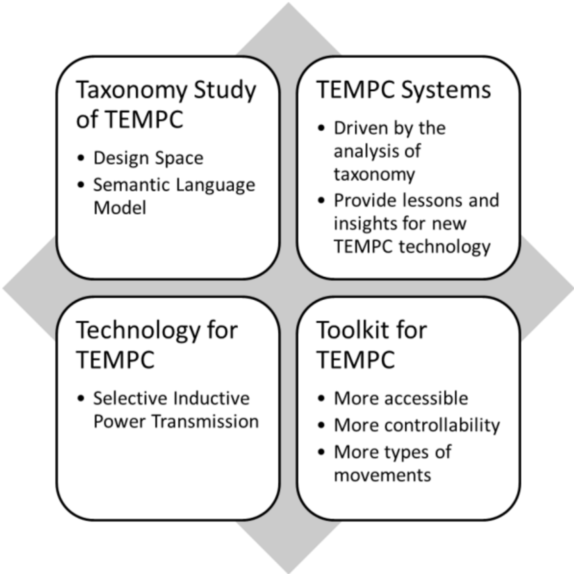

Figure 1.3: Contributions of the thesis

The first contribution lies on the construction of the taxonomy for TEMPC, which consists of Question-Options-Criteria (QOC) design space and semantic model. I followed the process of Design Space Analysis (Question, Option, Criteria) [57] to develop the design space. I further defined a semantic model for TEMPC based on the method introduced by Stu Card et al [12]. The taxonomy demonstrated the capability of modeling and analyzing existing TEMPC systems with the QOC-based design space and the semantic model. The analysis of the taxonomy further consolidated the problems identified in the current TEMPC research and drove the development of new TEMPC systems.

Secondly, two TEMPC systems were developed driven by the analysis of the taxonomy. More importantly, the study on the user experience of these two systems provided valuable insights and lessons for new technologies for TEMPC. The system presented in Chapter 4 recognizes different types of paper folding and paper movement based on natural feature tracking. A simple game application, Origami Tower, was developed using this algorithm, allowing players to create virtual content using origami. As outlined in Chapter 5, Snap-n-Fold virtually generates origami patterns based on real-life objects. Details will be presented in Chapter 4 and Chapter 5.

Thirdly, I developed the technology of selective inductive power transmission (Chapter 6), driven by the study of the two TEMPC systems above. This new technology automates physical paper movements with embedded hardware in paper material. Its advantage can be justified in that instead of requiring complicated wire connections to an external power source or isolating paper interaction from users, this method of integrating selective inductive power transmission with paper tends to eliminate physical power connection to the TEMPC. The technology of selective inductive power transmission provides a solution on the problem of accessibility of TEMPC systems.

Last but not least, I developed AutoGami (Chapter 7), a toolkit for designing automated movable paper craft using the technology of selective inductive power transmission with better controllability and accessibility. It allows users to design and implement automated movable paper craft without any prerequisite knowledge on electronics and supports rapid prototyping. Design workshops where AutoGami was deployed showed its feasibility in supporting engagement and creativity with better learnability and usability.

1.4 Outline

The ensuing parts of the thesis are organized as follows:

In Chapter 2, I provide a literature review on the existing the research on TEMPC. I divided the existing projects on TEMPC into two categories: single-function system or customizable toolkit. With *single-function systems*, I mean the related work in which the researcher already defined the shape and the movement of paper craft, and the end-users could not customize the output, or do not participate in the design and the creation of the technology-enhanced movable paper craft. Therefore, the category of single-function systems of technology-enhanced movable paper craft includes the software algorithm of recognizing paper movements (folding) and the demonstration of technology-enhanced movable paper craft. The toolkits here provide facilities that allow users to customize the shapes and the movements of paper craft as input and output. At the end of Chapter 2, I discuss the drawbacks of the current research on technology-enhanced movable paper craft as the motivation for my research.

Chapter 3 presents, in detail, my research contributing to the taxonomy for technology-enhanced movable paper craft. Following the method of QOC-based design space [57], I defined four design questions for TEMPC and the design options for each question based on the literature review in Chapter 2. Finally, I defined the design criteria based on the survey feedback from paper craft artists. The design space can model the existing TEMPC systems based on the design questions and the design options and analyze them according to the fulfillment of the design criteria. Furthermore, I developed a semantic model for technology-enhanced movable paper craft. The existing projects on technology-enhanced movable paper craft are analyzed using this model and placed into a table for technology-enhanced movable paper craft. With the analysis of the taxonomy, blind spots are found for possible research opportunities for new technologies to support TEMPC. The research gaps can be categorized into input and output units for TEMPC, and this motivated me to explore new TEMPC systems, presented in Chapter 4 and Chapter 5.

Chapter 4 presents the research results on new technologies for enhancing paper craft movement as input and demonstrates the capability of using the design space for inspiring new systems and technologies for TEMPC. The new system recognizes different types of paper folding based on natural feature tracking. It advances the existing research to a more natural interactive technique using paper. The user study of this system indicates that users prefer using paper, especially old newspaper or waste paper, as a medium for the system, and users prefer more tangible controllability than just watching VR animation. Chapter 5 continues the exploration of new systems based on the taxonomy of TEMPC. I present the research on generating paper craft movement as output, using Snap-n-Fold for virtually generating origami patterns based on real-life objects. The study of the user experience on Snap-n-Fold provided important lessons which show that users prefer TEMPC systems that allow them to create and control their paper craft and that an easy-made paper craft is preferable to complex origami. These insights and lessons provided in Chapter 4 and Chapter 5 motivated the development of new technologies for TEMPC presented in Chapter 6.

Chapter 6 introduces the technology of selective inductive power transmission and its integration with paper material. Through alternative electromagnetic field, the power transmitter can be controlled to activate different receivers selectively in the context of wireless power transferring with multiple receivers. This technology reduces the complexity of embedded hardware in paper craft and facilitates the creation of automated movable paper craft. Two different methods of selective inductive power transmission were developed and utilized for different purposes for technology-enhanced movable paper craft. Based on the comparison of the two prototypes, the suitable one was selected to further develop a toolkit for creating TEMPC in Chapter 7.

Chapter 7 introduces AutoGami, a toolkit for designing automated movable paper craft using the technology of selective inductive power transmission. It has hardware and software components that allow users to design and implement automated movable paper craft without any prerequisite knowledge on electronics and supports rapid prototyping. Design workshops where AutoGami was deployed showed its feasibility in supporting engagement and creativity as well as its usability in storytelling through paper craft, rapid prototyping of product design, and interaction design such as human-robot interactions.

Chapter 8 concludes the thesis by answering the research questions with the research results presented above. In addition, future directions on technology-enhanced handicraft will be discussed.

Chapter 2 Literature Review Technology-enhanced Movable Paper Craft

This thesis research on technology-enhanced movable paper craft is highly motivated by the various forms of traditional movable paper craft. With its cultural and aesthetic value, paper craft has attracted much interest from artists, scientists, educators, and so on. Traditional paper craft provides inspiration and motivation for HCI researchers to explore how to enhance paper-based interaction using digital technology. As digital technology emerged, HCI researchers started looking at how to enhance the conventional usage of paper material with computing technology. They have invented paper-like digital documents for writing and drawing [3, 23, 27, 35, 42, 45, 50, 51, 54, 63, 81, 85, 87, 88, 89, 96, 98, 99], and paper-based crafting interaction, such as origami interaction [25, 37, 39, 61, 79], pulp-based paper computing [14], etc. All these research efforts have led to the development of a new research area, Paper Computing [40].

In this chapter, I present a literature review in Paper Computing, mainly focusing on technology-enhanced movable paper craft. I first review the single-function systems of technology-enhanced movable paper craft. With *single-function systems*, I mean the related work in which the researcher already defined the shape and the movement of paper craft, and the end-users could not customize the output or do not participate in the design and creation of the technology-enhanced movable paper craft. Therefore, the category of single-function systems of technology-enhanced movable paper craft includes the software algorithm of recognizing paper movements (folding) and the demonstration of technology-enhanced movable paper craft. In the second part of the literature review, I evaluate the existing toolkits that allow users to create technology-enhanced movable paper craft. The methods used for creating the single-functioning systems of technology-enhanced movable paper craft will also be included in this part of the study. The toolkits here provide facilities that allow users to customize the shapes and the movements of paper craft as input and output.

In each part of the literature review, I further divide each existing work on technology-enhanced movable paper craft into two parts: sensing paper-craft movement as input and generating paper-craft movement as output, according to the two main components of human-computer interface [15], input and output. Therefore, I summarize each existing work based on the input and the output technologies. Furthermore, I compare these systems and tools based on the accessibility, usability, and controllability for end-users, and the variety of the enhanced paper movement. In the end of Chapter 2, I present a discussion on the current stage of technology-enhanced movable paper craft, which further motivated this thesis research on developing new technologies to enhance movable paper craft.

2.1 Single-Function Systems on Technology-enhanced Movable Paper Craft

2.1.1 Recognition of Folding Process from Origami Drill Books

By using the technology of computer vision, Hiroshi Shimanuki et al. [79] presented the algorithm to recognize and recreate the folding process of origami based on illustrations of origami drill books. This algorithm analyses the procedure in the origami drill book, divides the steps intelligently based on the special symbols for origami, and finally understands the steps for origami making to generate virtual origami in 3D animation.

2.1.2 Estimation of Folding Operations Using Silhouette Model

In this project, Kinoshita et al. [41] developed an algorithm for estimating the folding based on the difference between the shapes of a piece of paper before and after a folding process is made. They used the information of the edges and vertices in the camera images of paper folding to estimate the position of folding line and the direction of folding. The algorithm requires a set-up environment with black background and bright-colored paper, and the user needs to have an extra gesture to indicate the end of the folding process to trigger the start of the estimation.

2.1.3 Recognition and modeling of paper folding configuration using 2d bar code

Jun Mitani [61] introduced an algorithm for real-time transference of physical paper-folding into virtual animation by using special paper printed with visible 2D bar codes. The 2D bar codes are printed in both sides of the paper so the folding operation can be identified by calculating the position relationships of the bar codes from the real-time camera image. Similar to the work from Kinoshita et al. [41], the recognized folding here is represented in the form of VR animation.

2.1.4 Foldable User Interface

In Foldable User Interfaces [25], David Gallant et al. introduced sheets of paper that are augmented with IR-reflectors whose positions and orientations can be tracked by camera to allow users to manipulate digital information. The authors propose eight different movements that can be performed using FUI (Thumb Slide, Scoop, Top Corner Bend, Hover, Fold, Leafing, Shake, Squeeze). Based on the characteristics of these movements, we can summarize that FUI supports the recognition of these three basic movements as:

- 2D linear movement: Thumb Slide, Hover, Shake

- Fold: Fold

- Bend: Scoop, Top Corner Bend, Leafing

2.1.5 Origami Desk

Developed by Wendy Ju et al. [39], Origami Desk is an interactive installation that integrates multi-modal interaction technologies and techniques in new ways to instruct users in folding origami paper into boxes and cranes. It shows users how to fold through video clips projected on the desk and detects user folding using swept-frequency sensors and radio-frequency identification (RFID) tags embedded in the paper. Based on the detection of user folding, Origami Desk corrects the folding process by showing the instructions in real time on the desk.

2.1.6 Programmable Hinge & Interactive Paper Devices

Programmable Hinge [101] is one of the early demonstrations of integrating paper craft and computing technology. One of the prototypes in Programmable Hinge employs shape-memory wire as an actuator, where two pieces of SMA wire were embedded in the paper structure of the hinge to control the open and close of the hinge by programming the microcontroller. Following the method of Programmable Hinge, Greg Saul et al [76] presented a paper robot in Interactive Paper Devices. Paper robots are standard paper craft models with SMA wires connecting different parts of the body, and the SMA wires are controlled by the microcontroller to generate bending movements.

Although Programmable Hinge demonstrated the possibility of integrating technology and craft with a bulky system connected, it is the first system that introduced the concept of *Computationally-Enhanced Crafts*, which directly inspires the research in this thesis.

2.1.7 Oribotics & Adaptive Blooms

Oribotics [26] and Adaptive Blooms [29] are two artistic installations that trigger the blossom of origami flowers according to audience gesture input and the distance between the audience and the installation. In both installations, motors were embedded within the origami flower and drive the open and the close of the flowers. An ultra-sonic sensor is attached to each origami flower to sensor the interaction by the audience.

2.1.8 Electronic Popables

Electronic Popables [71] demonstrates the possibility of enhancing pop-up books with embedding technologies, such as LEDs, potentiometers, switches, bending sensors, SMA, etc. Various electronic components are mapped to and embedded in the metaphors of different structures in the pop-up book. For instance, a switch is integrated with the pull-tab bar in a book to close the electronic circuit and light up LEDs, and rotational potentiometers are attached to paper wheels while SMA are controlling the open and close of the pop-up structure.

2.1.10 Move-it

For using movable paper craft for more serious purposes, Kathrin Probst et al. [69] developed Move-it, a system that combines the affordances of note-taking on paper with the capabilities of computer systems. It combines Post-It notes with a shape-memory-alloy-enhanced paper-clip, which can be moved and thus give active feedback to the user as the event notification.

2.2 Toolkits for Technology-enhance Movable Paper Craft

2.2.1 Easigami

Easigami [37] is a tangible toolkit which embeds potentiometers on the edge of paper so that users can construct different shapes of the model by combining paper and the model, which is then reflected in a 3D virtual representation. The core components in Easigami are a set of hinges with embedded potentiometers that sense the angle of folding. The hinge connects two polygon pieces and forms a network of polygons with other hinges with similar connections of two polygons. In the early version of Easigami, users needed to construct the design of the network in the Easigami 2D

Pattern Builder and then follow the layout to build up the physical model. Later, the toolkit was improved by adding microcontrollers to all the hinges and polygons. Therefore, the toolkit itself can sense the structure of the polygon network and communicate with the computer through serial connection.

2.2.2 Pulp-based Computing

Marcelo Coelho et al. [14] developed a series of techniques, called pulp-based computing, for building sensors, actuators, and circuit boards that behave, look, and feel like paper. Pulp-based computing embeds electro-active inks, conductive threads, and smart materials directly into paper during the papermaking process and forms new composites of paper computing. The techniques related to movement within pulp-based computing are embedding bending sensors and SMA into paper material to trigger bending movements through microcontroller.

2.2.3 Animated Paper

Animated Paper [43] is a prototyping toolkit which combines paper, SMA, retro-reflective material, and copper foil. It allows users to print out the paper craft and attach SMA wire and other materials to create an enhanced movable paper craft. Users then put the enhanced paper craft into a laser control system which allows motion control of the SMA-enhanced paper. It requires a high-power laser generator which is expensive and not secure for end-users, but Animated Paper provides a new possibility of enhancing movable paper craft with SMA wire as output by precise controlling mechanism of laser.

2.2.4 Animating Paper using SMA

In the project of Animating Paper using SMA, Jie Qi et al. [70] summarized four types of folding and bending mechanisms that can be implemented using SMA. They further organized a workshop to teach participants how to attach SMA to paper cranes and trigger wing flapping with batteries. The results from the workshop showed that this technique of integrating SMA and paper craft could raise the interest of learning engineering skills, although it also takes time to create a successful integration as most participants did not have enough experience with electronics.

2.2.5 Popapy

Similarly, Kentaro Yasu et al. [102] invented Popapy, a postcard that transforms into a paper craft model after being heated by a microwave oven. It combines paper, heat shrink sheet, and thin aluminum sheet. The aluminum sheet provides heat to the heat shrink sheet efficiently, and the heated heat shrink sheet shrinks and the paper bends, allowing the paper model to stand. Popapy also provides a software interface that allows user to manipulate the size of paper, heat shrink sheet, and aluminum sheet, and preview the way that the paper transforms.

2.3 Summary

In this thesis, I mainly focus on the usage of paper as crafting material in interactive systems. The existing work can be sorted into two categories: single-function systems or toolkits, and each existing work contains either the input technology that sense the paper-craft movement or the output technology that generates the paper-craft movement, or both. A set of possible technologies for enhancing movable paper craft can be summarized based on this literature review; each system can be analyzed in terms of input movement, output movement, input technology, and output technology, as shown in Table 2.1.

Table 2.1: Summary of literature review based on input and output

Name	Input Movement	Input Technology	Output Movement	Output Technology
Recognition of Folding Process from Origami Drill Books [79]	Folding steps in books	Camera Image Processing	Folding	VR animation
Estimation of Folding Operations Using Silhouette Model [41]	Folding	Camera Image Processing	N/A	N/A
Recognition and modeling of paper folding configuration using 2d bar code [61]	Folding	Camera Image Processing	Folding	VR animation
Foldable User Interface [25]	2D linear movement, fold, bend	IR Camera, paper with IR markers	N/A	VR animation
Origami Desk [39]	Folding	RFID tag & reader	Instructions of folding crane and box	VR animation
Programmable Hinge [101] & Interactive Paper Devices [76]	N/A	N/A	Folding, bending	SMA
Adaptive Blooms [29] & Oribotics [26]	N/A	N/A	Folding	Motor
Electronic Popables [71]	2D sliding, 2D rotation, bending	Switch, potentiometer, bending sensor	Folding	SMA
Move-it [69]	N/A	N/A	Bending	SMA
Easigami [37]	Folding	Potentiometer	Folding	VR animation
Pulp-based Computing [14]	Bending	Bending sensor	Bending	SMA
Animated Paper [43]	N/A	N/A	2D linear movement, bending	SMA, laser
Animating Paper using SMA [70]	N/A	N/A	Folding, bending	SMA
Popapy [102]	Folding, Pop-up	VR simulation	Heat-shrink rubber, Heat	Folding, Pop-up

In the work of sensing paper craft, the first attempt is using the technology of computer vision, the most used technology of sensing paper-craft movement, as input. Most of the existing methods recognize real-life paper crafts as input methods to manipulate digital contents but there are special requirements in most of them, such as special paper printed with visible or invisible markers or well-made 3D models which require users to have professional skills in 3D modeling. However, very few studies attempted to use ordinary paper, which is easily accessible in daily life. Previous approaches required special set-up of the environment, such as high-contrast foreground and background, and special markers printed on the paper. These requirements caused a problem of accessibility of the TEMPC systems.

In the early day of generating paper-craft movement, VR animation and simulation were the most common technologies [25, 37, 39, 41, 79]. Recently, shape-memory alloy (SMA) has become widely used because of its ease of integrating with paper material [43, 70, 71, 101]. However, one common disadvantage is that the paper-based device requires a complex circuit to be embedded in the paper craft, which require users to have engineering skills to create their own technology-enhanced movable paper craft, revealing the problem of controllability and accessibility in TEMPC.

In addition, it is easy to ask questions about the exploration of the design space based on these existing studies. Most of the current TEMPC systems focus on folding and bending: Do these prototypes represent most of the possibilities of technology-enhanced movable paper craft? What are other possible new designs that could be inspired and generated from these prototypes? In order to address the problem of diversity of movement in TEMPC, I studied the taxonomy for technology-enhanced paper craft. Although many efforts have been shown in interactive paper craft, this sub-topic of paper computing can still benefit from a theoretical taxonomy, which provides a clearer overview of the existing projects and inspires possible innovation. In the next chapter, I discuss the results for generating the design space for technology-enhanced movable paper craft, supported with the analysis of existing projects using the taxonomy.

Chapter 3 Taxonomy of Technology-enhanced Movable Paper Craft[1]

As stated at the end of Chapter 2, most of the current TEMPC systems focus on a single type of movement, mainly folding and bending. More types of movement enhancement can be inspired by the study of the taxonomy and the design space of traditional movable paper craft with technological enhancement. In this chapter, I present my first contribution: the taxonomy of technology-enhanced movable paper craft. The analysis of the taxonomy for TEMPC serves as the theoretical foundation of this thesis by modeling existing TEMPC systems, spotting the possibility of improvement, and driving the design of new TEMPC technologies and systems.

As shown in Figure 3.1, the taxonomy consists of the design space and the semantic language model of technology-enhanced paper craft. I specifically focused on movable paper craft, which doesn't include cutting and gluing, since cutting and gluing require other tools, such as scissors.

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[1] Publication

1. Kening Zhu and Shengdong Zhao. 2013. AutoGami: a low-cost rapid prototyping toolkit for automated movable paper craft. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13). ACM, New York, NY, USA, 661-670.
2. Kening Zhu. 2012. A framework for interactive paper-craft system. In Proceedings of the 2012 ACM annual conference extended abstracts on Human Factors in Computing Systems Extended Abstracts (CHI EA '12 Student Competition). ACM, New York, NY, USA, 1411-1416.

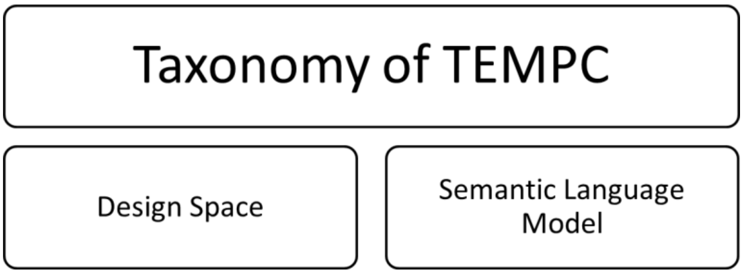


Figure 3.1: The taxonomy of TEMPC consists of the design space and the semantic language model.

In the remainder of the chapter, I first discuss the construction of the design space for TEMPC, including design questions, design options, and design criteria, followed by examples of using the design space to analyze existing TEMPC systems. Subsequently, I present the design of the semantic model for TEMPC systems and analyze and compare existing TEMPC systems using the semantic model. Finally, I discuss how the taxonomic analysis further consolidated the problems in current TEMPC systems and motivated me to develop new systems to explore the taxonomy of TEMPC.

3.1 Definition of Taxonomy, Design Space, and Semantic Model

By definition from Webster [18], *taxonomy* means a method or scheme of classifying things or concepts, including the principles that underlie such classification. Therefore, I present the taxonomy of technology-enhanced movable paper craft as a way of classifying a system that enhances movable paper craft with digital technology. The principal guideline of designing taxonomy, proposed by [75], is “to organize the taxonomy as a set of independent, ‘orthogonal’ sub-taxonomies (facets or perspectives), which behave as coordinates in a multidimensional space.” On the other hand, *design space* [86] is defined as “a structured combination of design options having assigned a finite set of design options values that support the stakeholder’s design decisions during the development life cycle of user interfaces.” Here a design option is defined as a design factor which effectively and efficiently supports the design cycle towards a final system while ensuring the final quality. For each design option, a finite set of design option values denote the various alternatives to be considered simultaneously when deciding a design option. Therefore, we can consider the design space as an effective representation of the taxonomy for technology-enhanced movable paper craft (TEMPC).

There are a few advantages of defining a design space [86] for TEMPC:

- When the design space is clearly defined, the development process is structured in terms of selections, requiring less design effort on trial and error.

- Design space is descriptive by nature. All design options are documented and allow the summarizing of any design in terms of design option values. These values have been identified and defined based on observation and abstraction of the TEMPC system and by introspection over the personal knowledge regarding the systems.

- Within the design space, several different designs of TEMPC may be analyzed and compared based on the design options considered in their development so as to assess the design quality in terms of factors like accessibility, variety of movements, controllability of movements, etc.

- The design space allows for the discovery of potentially new values for the existing design options or to introduce new design options associated with yet under-explored design aspects.

For the semantic model, I followed the definition provided by Stu Card et al. [12]. They defined the semantic model as "an analytic language system with a set of primitive languages based on orthogonal properties, and a set of composition operators.” This model provides a method for highly abstracting a device as a mathematic formula.

3.2 Methods of Constructing Design Space for TEMPC

To construct the design space for TEMPC, I followed the method of QOC (Question, Option, Criteria) [57] due to its efficiency in generation and implementation. The major elements of QOC-based design space are:

- *Design Questions*: Design questions pose key concerns or issues to be addressed in each step of designing and implementing the system of TEMPC.

- *Design Options*: Design options are possible answers to the design questions.

- *Design Criteria*: Design criteria are the basis and the rationale for evaluating and choosing within different design options.

In the context of designing TEMPC systems, designers need to consider the selections of the movements of the paper craft, and the technologies, based on certain criteria. Through literature review of existing TEMPC systems and a survey with experienced paper-craft artists, I derived a set of design questions, design options, and design criteria. Details of the QOC-based design space for TEMPC will be presented in Section 3.3. In addition, the usage of this design space for analyzing existing TEMPC systems will be demonstrated in Section 3.3.

In addition, I followed the sematic method used by Stuart Card et al. [12] in developing the design space of input devices to provide a clearer abstraction of the TEMPC system and visualize the design space more clearly. In the design space for input devices, Stuart Card et al. developed a semantic language model which consists of the primitive vocabulary of the design options and a set of composition operators, and visually represent the taxonomy in the form of a table. Following a similar method, I developed the vocabulary for input movements and technologies, output movements and technologies, and the operators to form an abstract model of TEMPC systems and generate the taxonomy in a table view. Details will be presented in Section 3.4.

3.3 QOC-based Design Space for Technology-enhanced Movable Paper Craft

The QOC method of developing design space strongly relies on the definition of Design Questions, Design Options, and Design Criteria. In this thesis, I defined these three constituents for TEMPC design space mainly based on the literature review of existing TEMPC projects (Chapter 2) and consultation with experienced paper-craft artists.

3.3.1 Design Questions

As defined, there are two main components in a TEMPC system: technology and movement, and both of them can be used as input and output, as shown in Figure 3.2.

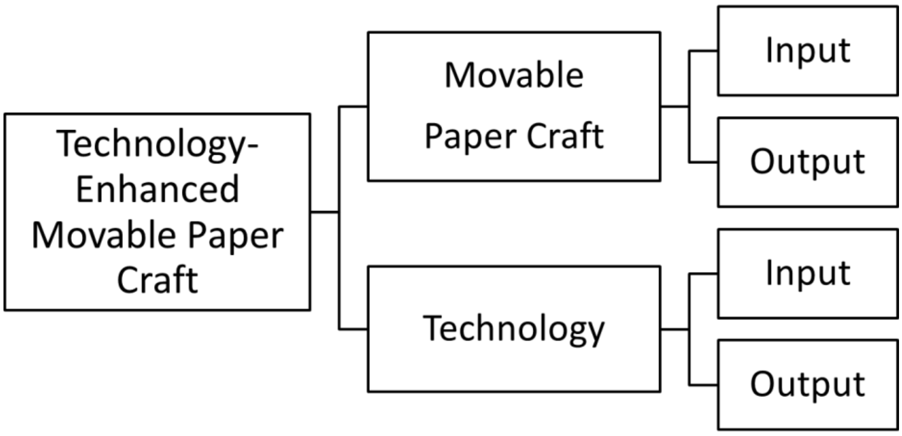


Figure 3.2: Input and output of TEMPC

It is clear that there are four essential elements needed to be considered for the creation of a TEMPC system:

- Input Movements

When creating a TEMPC system or demo with paper-craft movement as input, users need to consider what possible movements can be performed by the paper craft. They need a primitive vocabulary that covers as many options of movement as possible. Therefore, we can see one design question in the consideration of input movement for TEMPC systems:

Design Question #1: What are the input movements of paper craft?

- Output Movements

Similar to designing the input movements, users need to consider what the possible output movements are and what the style of output movement will be. Therefore, we have one design question for considering generating paper-craft movement as output:

Design Question #2: What are the output movements of paper craft?

- Technology for sensing the input movement

After deciding the input movements, users need to consider the feasible technologies to implement the sensing system to enhance the paper craft movement as input. In Chapter 2, I summarized a set of possible technologies that can sense paper-craft movements. Therefore, we need to answer the question of which sensing technology to choose:

Design Question #3: What are the technologies to sense the input movement?

- Technology for generating the output movement

Similarly, users will have to answer the question about how to generate the paper-craft movement as output:

Design Question #4: What are the technologies to generate the output movement?

In summary, the four main design questions for TEMPC are as shown in Figure 3.3.

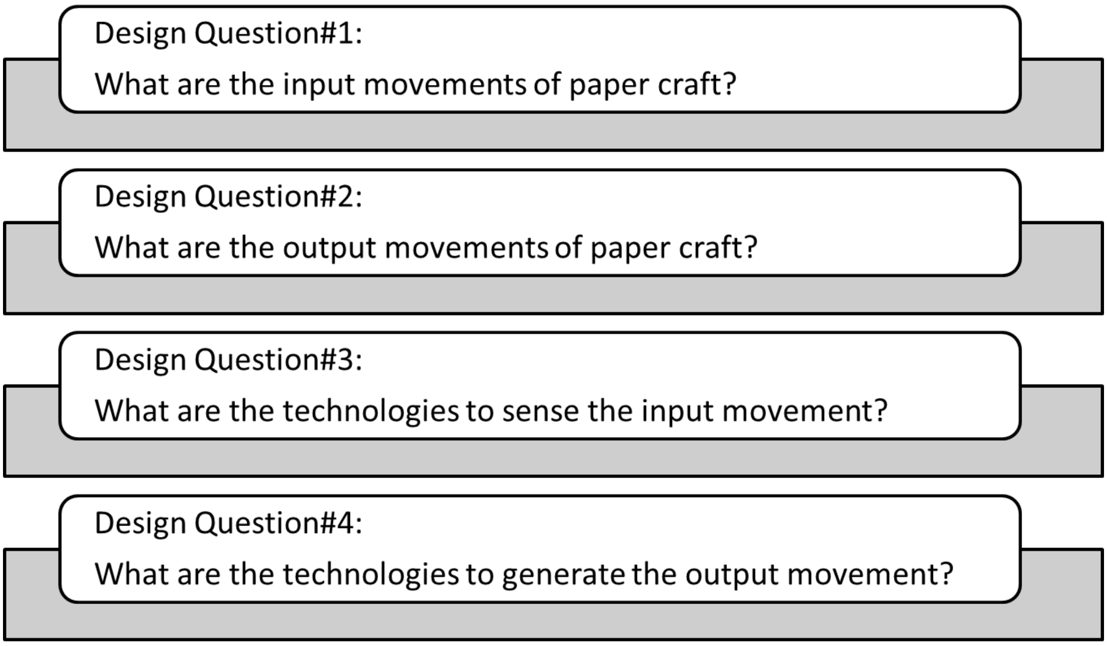


Figure 3.3: Four design questions for TEMPC

3.3.2 Design Options

After defining the design questions, we then need to generate the possible answers for each question, essentially the design options in the QOC-based design space.

3.3.2.1 Options for Design Question #1 & Design Question #2

The design options for choosing paper-craft movement as input or output should cover all possible paper craft movements. In order to generate a comprehensive vocabulary of paper craft movements, I conducted further review of the literature on traditional movable paper craft [38, 64] and developed a simple but complete classification for the movements of traditional paper craft. I 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 3.4).

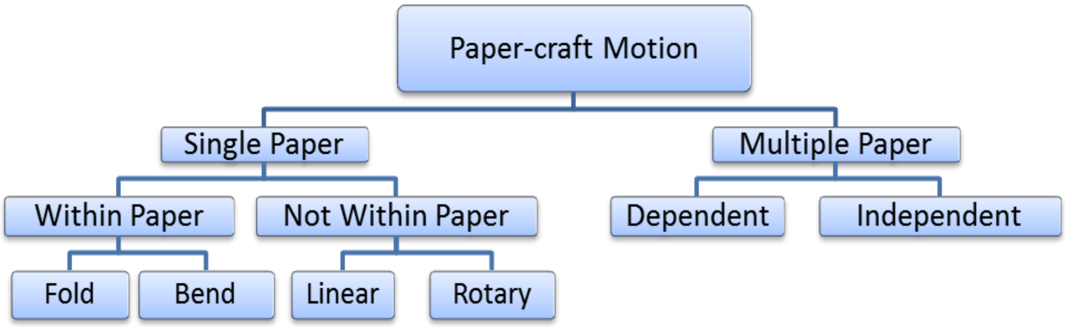


Figure 3.4: Classification of paper movement.

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.

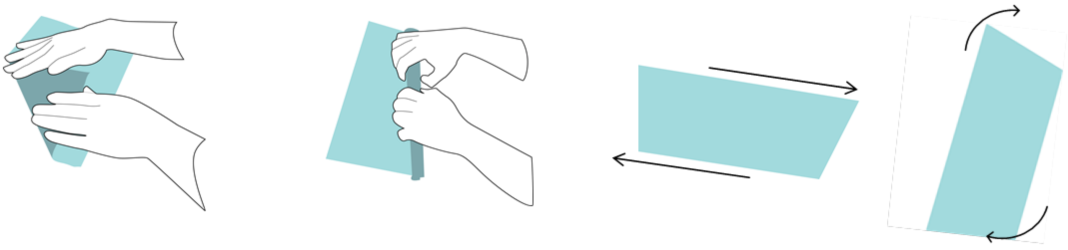
Fold - creates a crease; a combination of creases creates origami. Fold refers to folding in one direction or multiple directions (Figure 3.5a).

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 3.5b).

Not Within Paper – Movement that …. such as linear translation or rotation.

Linear refers to movement in 2D and 3D space (Figure 3.5c).

Rotation refers to the orientation of the paper craft. Movement along the axis can occur in 2D and 3D space (Figure 3.5d).

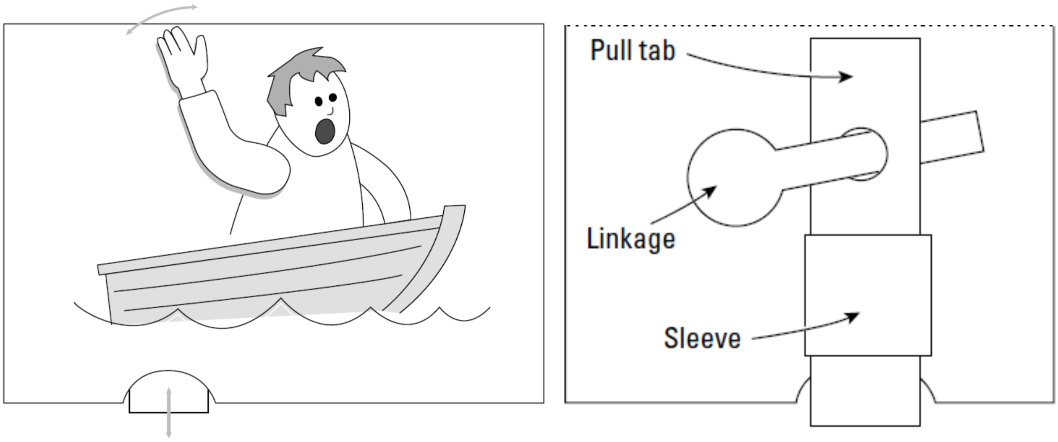


(a) (b) (c) (d)

Figure 3.5: Movement primitives of single piece of paper: (a) fold, (b) bend, (c) linear translation, (d) rotation.

Multiple Papers also has two subcategories:

Dependent - The movement of one paper can trigger the movement of another paper. This type of movement is common in movable paper craft [38] which uses traditional mechanical structures such as gears and pulling bars (Figure 3.6). In movable paper craft, we can equate dependent movement in terms of input-output relationship.



(a) (b)

Figure 3.6: An example of the dependent paper craft mechanism: (a) Pulling the tab lets the boatman's arm rotate, (b) back view of the mechanism

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

With the classification above, we can conclude that the design options for Design Question #1 (Q#1) and Design Question #2 (Q#2) are the complete vocabulary of paper-craft movement:

Design Options (Q#1 & Q#2) = [2D linear movement, 3D linear movement, 2D rotation, 3D rotation, one-directional folding, two-directional folding, one-directional bending, two-directional bending] (Figure 3.7).

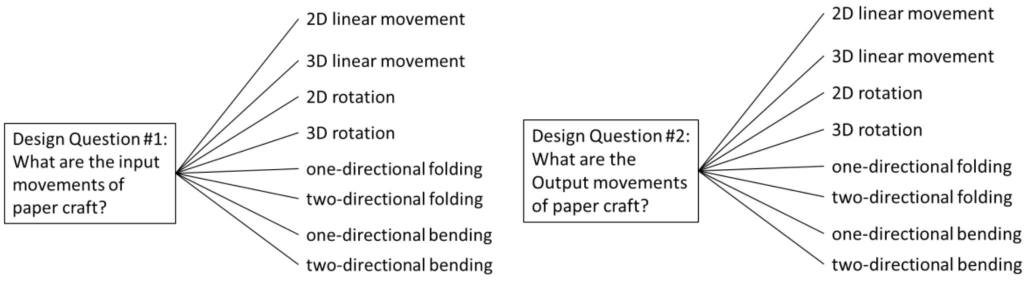


Figure 3.7: Design options for design questions #1 and #2.

3.3.2.2 Options for Design Question #3

Based on the literature of existing TEMPC research in Chapter 2, there are a few candidates for sensing movable paper craft as input. As shown in Figure 3.8, these possible technologies include Camera Image Processing, VR simulation, switch, potentiometer, bending sensor.

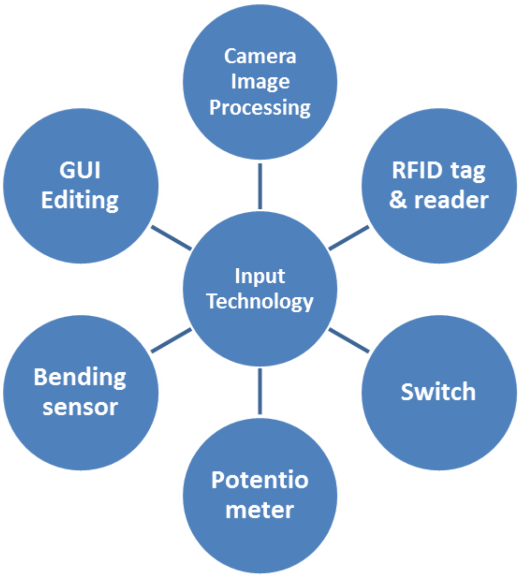


Figure 3.8: Input technologies used in existing systems.

Therefore, we can construct the design options for sensing technologies as:

Design Options (Design Question #3) = [Camera Image Processing, VR simulation, switch, potentiometer, bending sensor, RFID] (Figure 3.9).

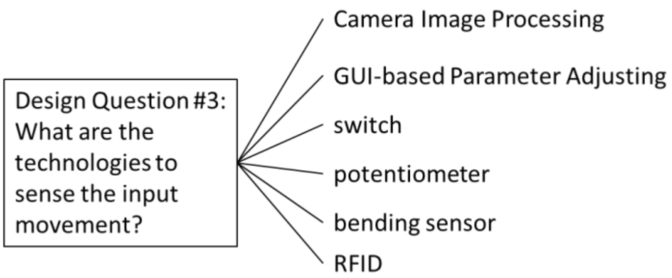


Figure 3.9: Design options for design question #3

As a point of clarification, these design options can be expanded as new technologies are invented.

3.3.2.3 Options for Design Question #4

We can also construct the design options for technologies to generate movable paper craft as output based on the review of existing systems of TEMPC (Figure 3.10).

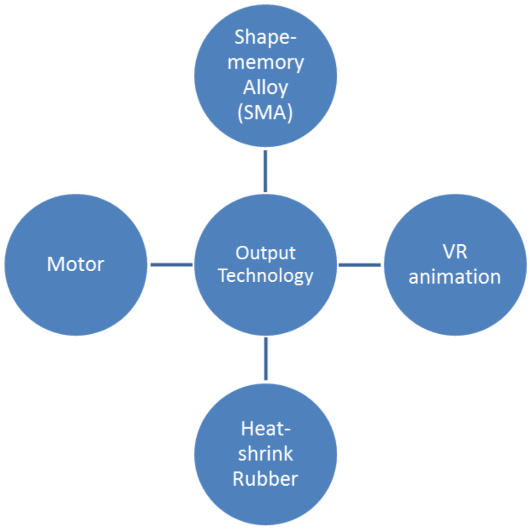


Figure 3.10: Output technologies used in existing TEMPC systems.

Design Options (Design Question #4) = [VR animation, motor, SMA with laser, Heat-shrink rubber with microwave] (Figure 3.11).

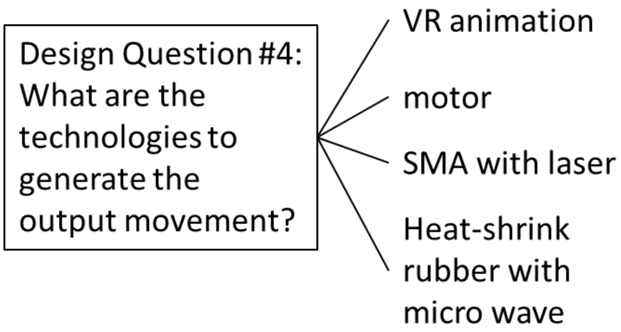


Figure 3.11: Design options for design question #4.

Similarly, this set of design options can also be expanded as new technologies emerge.

3.3.3 Design Criteria

Design criteria are for evaluating the design options for each design question, and it is easy to notice that the considered criteria are subjective. However, I tried to decrease the subjectivity level by first considering a set of proven properties that are being experimentally assessed and successfully used to evaluate several types of user interfaces [53], as summarized as below:

- Usefulness

As defined in [15], usefulness of the information technology is the degree to which a person believes that using a particular system would enhance his or her performance. Here, the usefulness of technologies that enhance movable paper craft refers to whether the technology is feasible to sense the paper movement or generate the paper movement.

- Ease to use

Fred Davis et al. [15] defined *ease to use* as “the degree to which a person believes that using a particular system would be free of effort," with the meaning of *ease* as “the freedom of difficulty or great effort." We can define the ease of use on TEMPC system as how much the system or the technology relies on the set-up of environment or device and the engineering knowledge of the end-users.

- Ease to learn

From the definition of ease to use, we can derive the definition of *ease to learn* as “the degree to which a person believes that learning how to use a particular system would be free of effort."

- Satisfaction

The satisfaction of using a system or technology refers to the user’s experience while using the system [15]. Related questions include whether users enjoy using the system, whether users would like to introduce the system to others, whether the system works the way user wants, etc.

Besides the standard criteria of designing user interfaces, the unique characteristics of movable paper craft should also be considered as important criteria while using digital technology for TEMPC. In order to understand what the important factors are in movable paper craft, I conducted an informal interview with 5 paper-craft artists who have more than 5 years of experience in making paper craft. Two of these artists are the core members of the Hong Kong Origami Association [93].

One artist, chairman of the Hong Kong Origami Association, said:

(Summarized and translated from Chinese)

> *Paper has its unique natural quality, which is thin, flexible, and fragile. By being fragile, I mean each piece of paper craft artwork looks naturally fit into the environment, and the aesthesic could be easily broken by introducing too many technologies. If you are going to put computers into paper craft, it is better to hide them carefully.*

Similar comments came from the other experienced paper-craft artist, who authored the best-selling pop-up storybook in Hong Kong:

> *Making real pop-ups gives me a lot of joys. The subtle and fragile movement of paper makes its unique beauty and magic. It would be acceptable only if the technology, the hardware, supports and keeps the nature of paper craft, instead of overwhelming it.*

In addition, all of the artists mentioned their concern about the cost of the technologies; they would prefer adding low-cost technologies to make their artworks more interactive to the audience.

By summarizing these comments, I defined two design criteria that need to be considered while enhancing movable paper craft with digital technologies:

- **Low cost**: The low cost of the digital technology gives high accessibility to artists.

- **Ease to integrate with paper material**: The ease to integrate with paper material refers to how much effort the artist expend to integrate the technology with their artwork and whether the enhancement keeps the natural beauty of the movable paper craft artwork.

Therefore, the final set of design criteria for technology-related design questions is as shown in Figure 3.12.

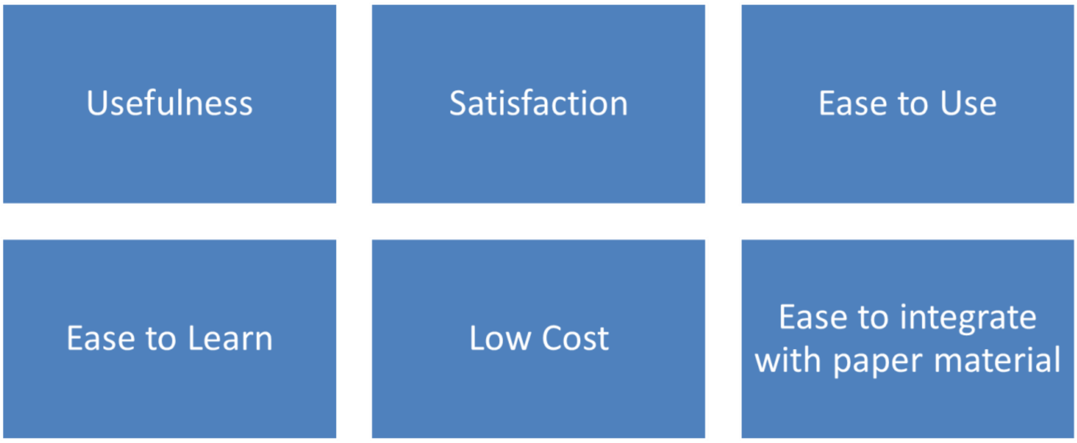


Figure 3.12: Design criteria for choosing technology-related design options.

3.3.4 Final Visualization of the QOC-based Design Space for TEMPC

QOC-based design space can be represented as a diagram divided into three columns (one for each element - questions, options, criteria) and the links between these elements. Each question is associated several design options. We can visualize the design space for TEMPC as shown in Figure 3.13.

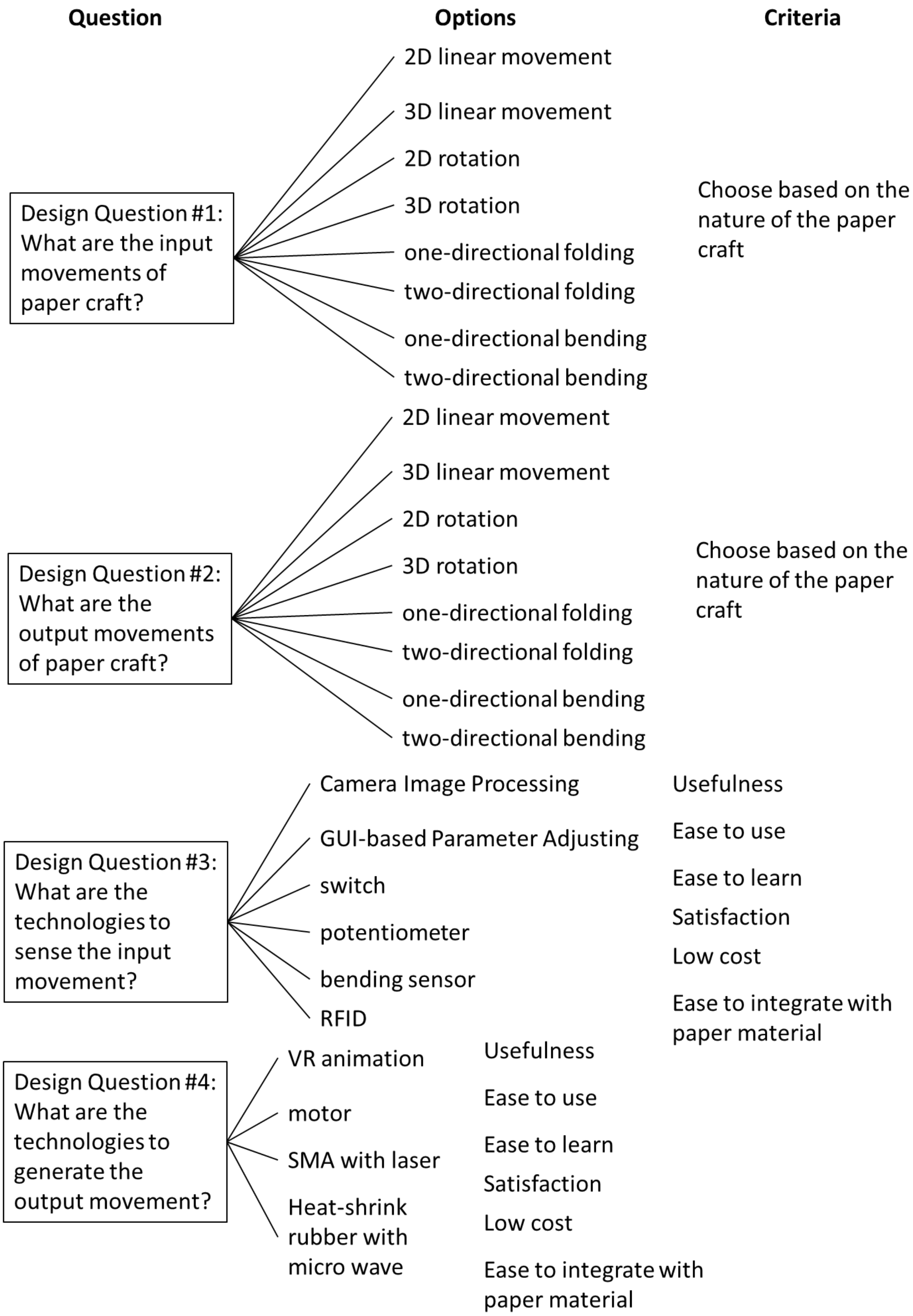


Figure 3.13: Visualization of QOC-based design space for technology-enhanced movable paper craft.

3.3.5 Analysing Existing TEMPC Systems with QOC-based Design Space

With this design space, we can analyze and model the existing TEMPC systems in visualization similar to Figure 3.13. In the visual model of QOC-based design space, the design option can be assigned to different criteria that favor (connected with a solid line) or do not favor (connected with a dotted line) these options. The adopted options are emphasized in a rectangle.

3.3.5.1 The Programmable Hinge

As shown in the Programmable Hinge [101], a hinge was rotated with the shape changing of shape-memory-alloy wires, and users need to program the microcontroller in order to control the movement of the paper hinge. As mentioned by the author, there are hardware and software issues in the Programmable Hinge system, such as the bulky size of batteries and circuits, high-level controlling language, etc. Although the Programmable Hinge is the first computationally-enhanced craft, it could not fulfill all the design criteria in the QOC-based design space. In addition, the Programmable Hinge only demonstrated the ability of generating automated movement, without sensing movable paper craft using digital technology. Therefore, we can summarize the abstract model of the Programmable Hinge as shown in Figure 3.14.

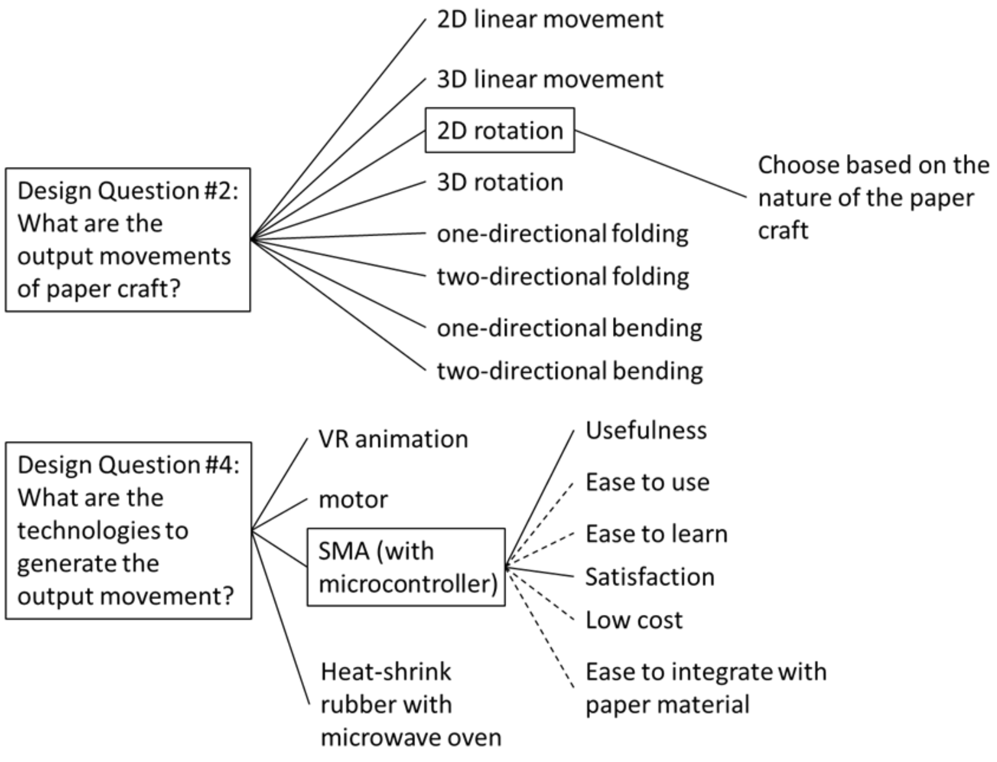


Figure 3.14: QOC-based model of Programmable Hinge

3.3.5.2 Animated Paper

In Animated Paper [43], shape-memory-alloy wires are attached on the paper craft and activated by high-power laser beam. Users control the laser beams by adjusting the parameters on a GUI software interface. Animated Paper can generate precise movements of paper craft, such as bending and linear translation movement, but it requires expensive and unstable devices that are not easily accessible to users, affecting its fulfillment of the design criteria. The QOC-based model of this system is shown in Figure 3.15.

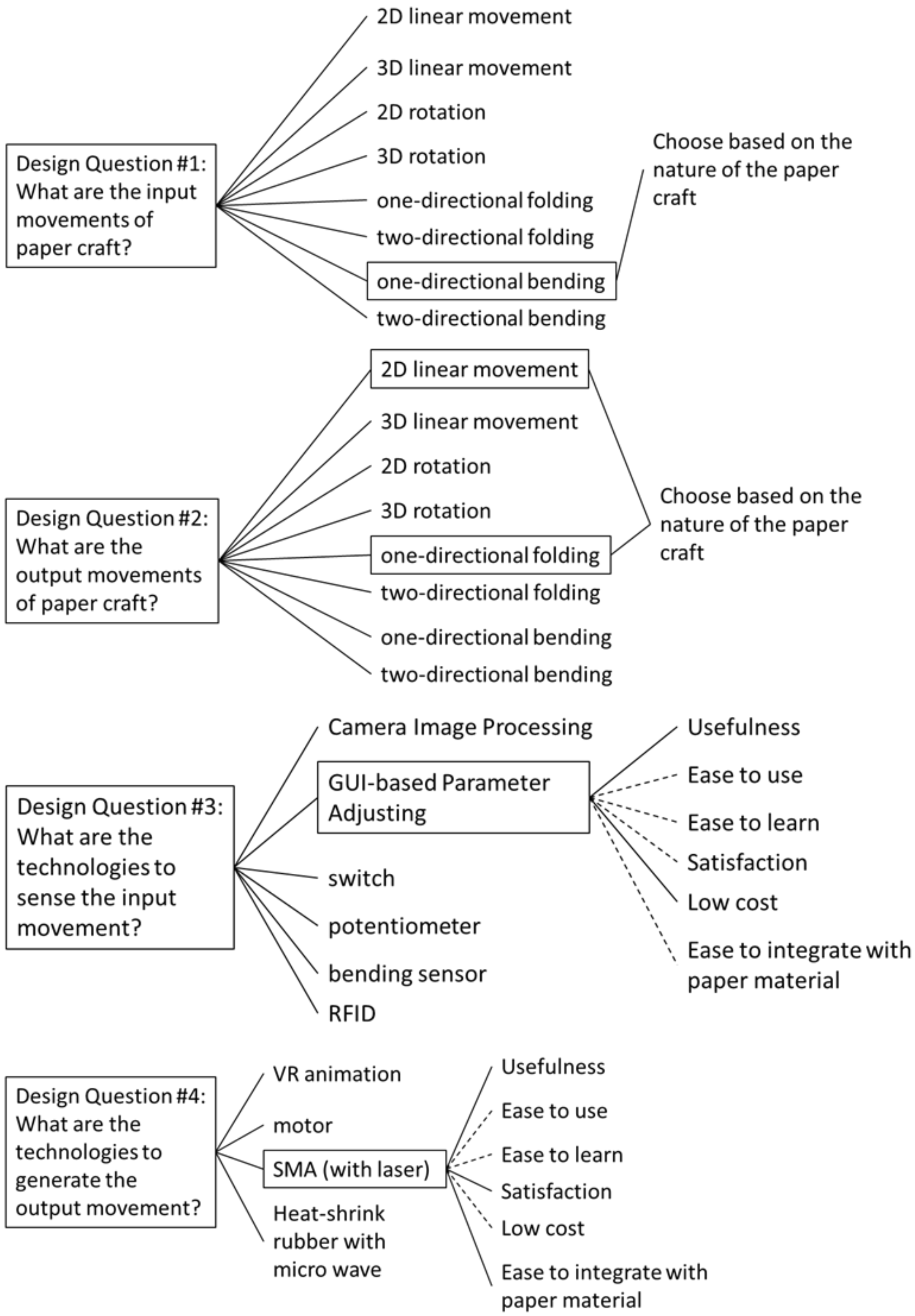


Figure 3.15: QOC-based model of Animated Paper.

3.3.5.3 Animating Paper with Shape-Memory Alloy

In the project of Animating Paper with Shape-Memory Alloy [70], researchers developed four mechanisms of paper movements and conducted a workshop to teach participants how to use soldering tools and electronic components to create wing-flapping paper cranes. However, not every participant could successfully create the wing-flapping paper cranes, and most of them spent a lot time on debugging the circuits due to a lack of knowledge of electronics. While the workshop increased the interest of learning electronics, we can see that the techniques introduced in this project are not easy to learn and easy to use for end-users. Based on this analysis, we model this project in Figure 3.16.

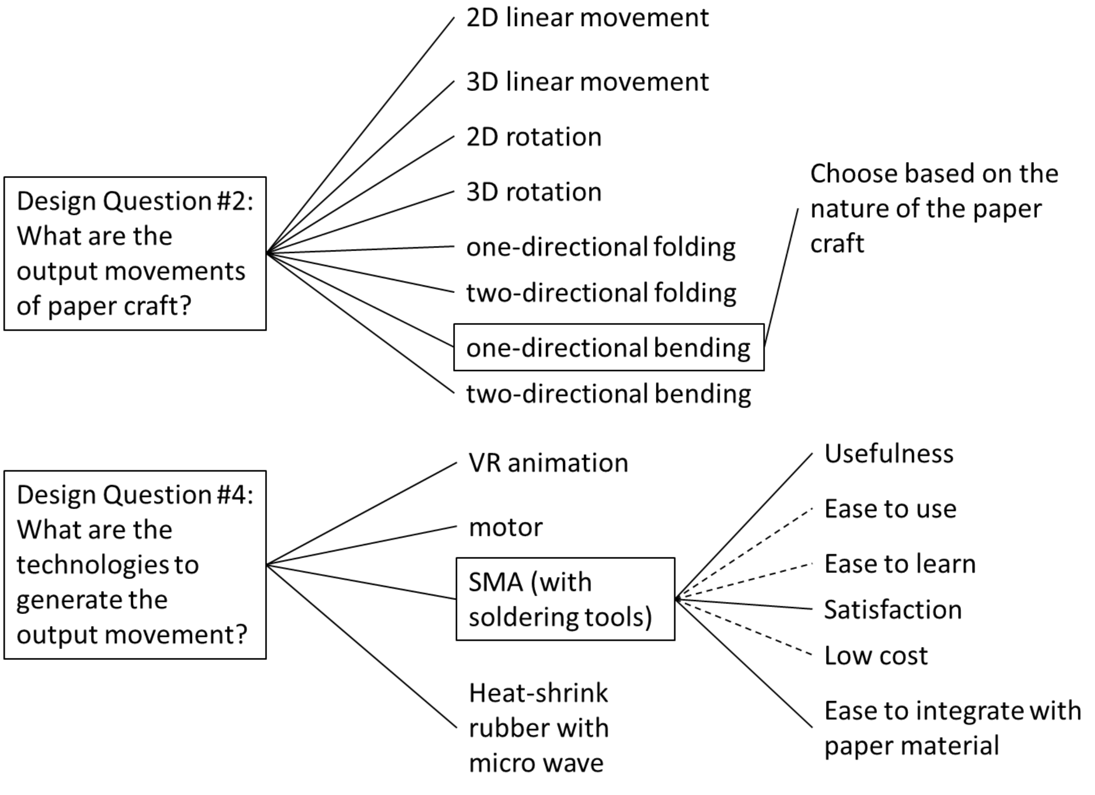


Figure 3.16: QOC-based model of Animating Paper with Shape-Memory Alloy.

3.3.5.4 Easigami

Easigami [37] is one of the best up-to-date TEMPC systems that was able to sense paper folding as input and generate 3D virtual models as output. Easigami (Figure 3.17) utilizes potentiometers embedded in the paper cardboards to detect the angles and the directions of the folding movement. Based on the connection and the folding angle of different cardboards, the system generates virtual models of the physical structure.

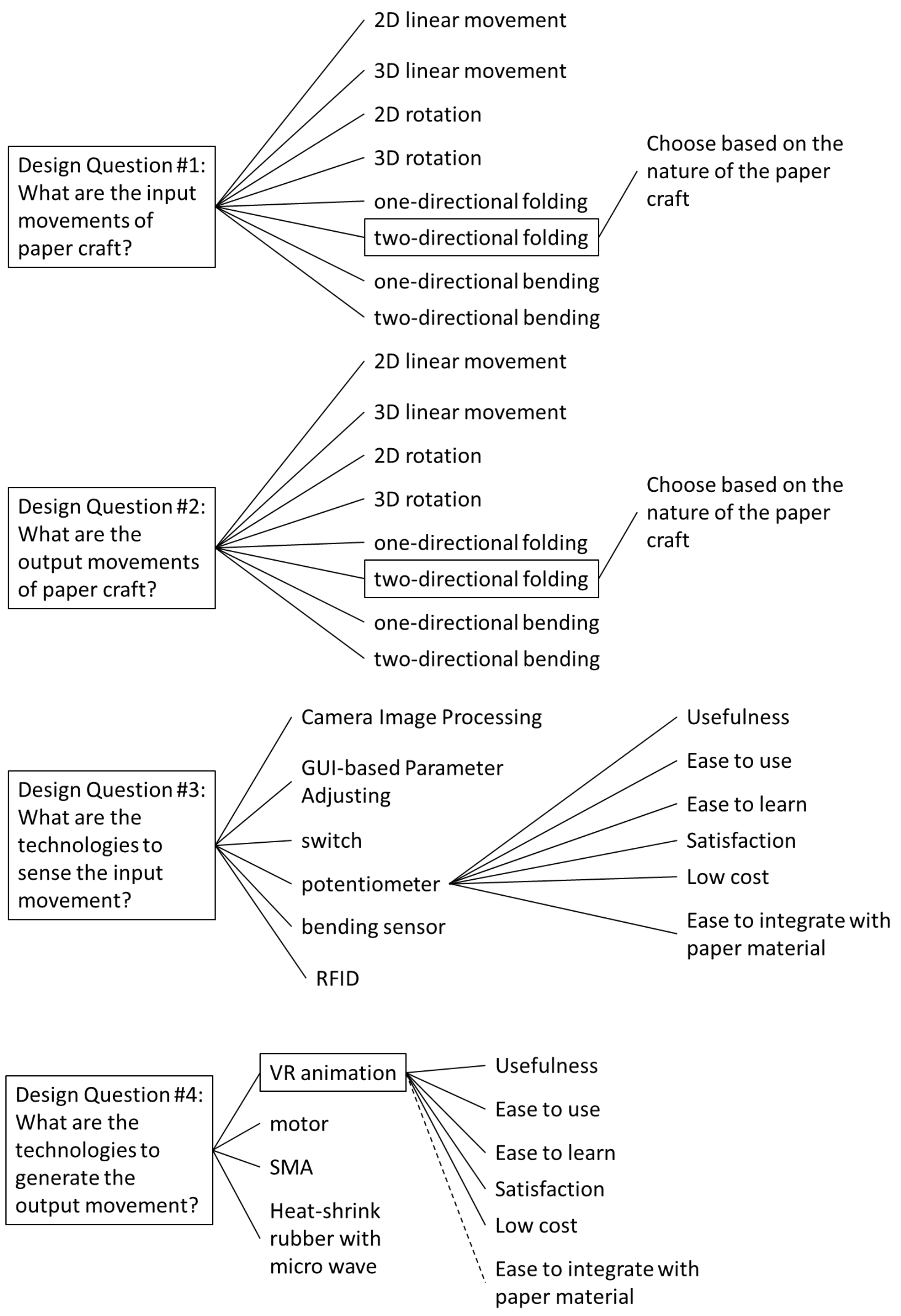


Figure 3.17: QOC-based model of Easigami.

Based on this QOC-based design space, we can generate the visual model for each existing work on TEMPC. Appendix A provides all the visual models for the existing TEMPC systems, which are generated based on the QOC-based design space. From these visualizations, we can see that for the technologies for sensing movable paper craft, hardware-based solutions, such as potentiometers, switches, and sensors, can fulfill the design criteria better than software-based solutions, which usually required special set-up of the environment or device. For generating movable paper craft, SMA is the most preferred technology for automated physical movement. However, most of the existing methods require technical skills, such as programming and electrical tinkering.

3.4 Semantic Model for Technology-enhanced Movable Paper Craft

While using the visualization of QOC-based design space is easy to model one TEMPC system, it is hard to compare the features of more than two systems due to the size of the visualization. Therefore, it requires another dimension in the taxonomy to compensate for this problem. Following the method by Stu Card et al [12], I designed a semantic model for analyzing technology-enhanced movable paper craft systems to provide a clearer view of the coverage of the design space by existing systems.

A technology-enhanced paper craft can thus 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 in the subcategories of *Within Paper and Not Within Paper* (Figure 3.5).

$MovementStyle$ 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 semantic model 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 the 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 to mode-changing of the system.

→ (dependent) shows the connection between input and output, where the starting point is the input methods and the end point is the output results.

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

We then used this semantic model to analyze the existing automated paper crafts as examples.

The Programmable Hinge [101] can control the rotation angle of the hinge through a microcontroller. Using the semantic model, we can model it as:

$$ProgrammableHinge = (Movement: 2DRotary, MovementStyle: Continous, R: \{\ \}, W: \{\})$$

In Animated Paper [43], SMA animates paper craft by bending, which causes it to move on a flat surface:

$$AnimatedPaper = (Movement: Bend, Linear, MovementSyle: Binary, R: \neg Bend \rightarrow \neg 1DLinear | \neg 2DLinear, W: \{\})$$

In Animating Paper with SMA [70], there is multiple bending and folding. Since they cannot be performed at the same time, the movements have an | (or) relationship:

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

In Interactive Paper Devices [76], the movement of the paper robot was triggered by bending the SMA.

$$InteractivePaperDevices = (Movement: Bend, MovementStyle: Binary, R: \neg Bend, W: \{\})$$

Electronic Popables [71] embedded switches, bending sensors, and shape-memory alloys in the paper pop-up structure. The linear movement of the pulling tab and the rotary movement of the paper wheel switch on the closed loop of the embedded circuit and activate the bending and folding movement of the pop-up.

$$ElectronicPopables = (Movement: Linear, Rotary, Bend, Fold, MovementStyle: Binary, R: \neg Linear | \neg Rotary \rightarrow \neg Bend | \neg Fold, W : \{\})$$

Pulp-based Computing [14] integrates bending sensors with paper pulp and creates a paper-like sensor.

$$PulpbasedComputing = (Movement: Bend, MovementStyle: Binary, R: , \neg Bend, W : \{\})$$

Oribotics [26] created a motor-driven paper folding structure which is sensitive to the user's distance. With the high-fidelity control of the motor, Oribotics can create continuous folding of paper craft. However, its input method is not based on paper-craft.

$$Oribotics = (Movement: Fold, MovementStyle: Continous, R: Fold, W : \{\})$$

Similar to Oribotics, Adaptive Bloom [29] demonstrated a matrix of origami flowers with embedded motors. By sensing the distance between the user and the matrix, the system opens the flowers continuously.

$$AdaptiveBloom = (Movement: Fold, MovementStyle: Continous, R: Fold, W : \{\})$$

Programmable Matter [31] uses more advanced embedded technologies, MEMS, to generate the automated folding movement of the paper-like memory. In the current stage, it only demonstrates the folding movement as the output.

$$ProgrammableMatter$$

$$= (Movement: Fold, MovementStyle: Continous,$$

$$R: Fold, W : \{\})$$

In Popapy [102], the aluminum sheet acts as an antenna to receive heat from a microwave oven and heats up the rubber to bend the paper. Users can adjust the angle of bending paper continuously through the software interface.

$$Popapy$$

$$= (Movement: Bend, MovementStyle: Continous, R: Bend, W : \{\})$$

Move-it [69] embedded shape-memory alloy into a paper clip to control the bending of the Post-it note to notify of the upcoming event.

$$Moveit$$

$$= (Movement: Bend, MovementStyle: Binary, R: Bend, W : \{\})$$

Table 3.1 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. A dashed line indicates the | (or) relationship between two movements, and the arrow indicates the input-output relationship between movements.

Table 3.1: Design Space of Technology-enhanced Movable Paper Craft

Not Within Paper					Within Paper				
Rotary Motion		Linear Motion			Bend		Fold		
2D	3D	1D	2D	3D	Single Direction	Multiple Direction	Single Direction	Multiple Direction	
		③	③		③⑪ ⑤ ④		⑥ ⑤② ④		Binary
					⑩		① ⑨	⑦⑧ ⑨	Continuous

①: Programmable Hinge [101]

②: Interactive Paper Devices [76]

③: Animated Paper [43]

④: Electronic Popables [71]

⑤: Animating Paper with SMA [70]

⑥: Pulp-based Computing [14]

⑦: Oribotics [26]

⑧: Adaptive Bloom [29]

⑨: Programmable matter by folding [31]

⑩: Popapy [102]

⑪: Move-it [69]

In summary, the semantic model shows the ability of presenting a system in a highly abstract model and comparing all existing systems clearly in one table. However, it does not clearly show the details of the decision in one particular technology, and this drawback can be covered using the model of QOC design space.

3.5 Summary

This chapter presented the analysis of the taxonomy for TEMPC systems, consisting of a QOC-based design space and a semantic model. The QOC-based design space demonstrated the capacity of modeling and analyzing existing TEMPC systems, showing what the possible design options are in the design space and how a system fulfills the design criteria. We can see that Camera Image Processing is the most popular method for input, but most existing systems could not fulfill the design criteria well by requiring special set-up in the systems. SMA (shape-memory alloy) is popularly used in generating output movement, but it is hard and expensive to use in order to provide better control. The semantic model allows us to abstract and compare all the TEMPC systems in one table. An empty space can be seen in Table 3.1, suggesting that current TEMPC systems do not explore all the possible movements and do not provide enough control on continuous paper craft movements. First, the number of movement types they support cover different and often limited number of cells in Table 3.1: Design Space of Technology-enhanced Movable Paper Craft Most of them only support binary movement (i.e., [14, 43, 70, 71, 76]). In Animating Paper with SMA [70], for instance, the movement is still quite primitive as it is only controlled by switching the power supply on and off; a power on/off pattern is used to flap the wings of a paper crane. Second, the support for designing movement is limited. Moreover, except for Interactive Paper Devices [76], others do not have a graphical user interface for designing movement. Third, these existing toolkits either support rapid prototyping without sufficient controllability and customizability (Programmable Hinge [101] and Animating Paper with SMA [70]), or require users to have electronic knowledge in order to create circuits for programming and controlling the movement of paper craft (Interactive Paper Devices [76]), such as skills on using soldering tools and computer programming [70]. Fourth, some use expensive and proprietary technologies (i.e., Animated Paper [43] uses a high-power laser for heating up the SMA), making them less accessible. These shortcomings result in these existing works not fulfilling the design criteria of ease to use and ease to learn.

In summary, the analysis of the taxonomy for TEMPC further detailed the problems identified in the literature review and spotted the research opportunities of new systems. In Chapter 4 and Chapter 5, I will demonstrate the capability of the taxonomy in driving and reasoning the development of new TEMPC systems by presenting two systems of sensing and generating movable paper craft. The study of user experience on these two systems provided important insights and lessons on user preference for TEMPC systems, which motivated the development of new technology.

Chapter 4 Sensing Paper craft as Input[2]

The analysis of the taxonomy in Chapter 3 identified the problems in current TEMPC systems. I first looked into the technologies of sensing the movements of paper craft to explore the possibilities in the proposed design space. While most of the existing technologies on sensing movable paper craft were based on camera image processing [25, 41, 61, 79], they usually required special set-up of the environment, such as high-contrast background and foreground [41, 79], paper with markers [25, 61], and special infrared camera [25], etc. In this chapter, I present the design and the implementation of a new system to sense paper movement as input based on camera image processing, which can reorganize linear translation, rotation, and folding of a piece of normal paper based on natural-feature tracking. The main contribution of this chapter lies with the user study of this method of origami recognition, which provides valuable insights on user preference on interacting with TEMPC systems.

4.1 Design with QOC-based Design Space

The motivation behind developing a new system for recognizing movable paper craft is to allow end-users to use movable paper craft as the control by mapping the movement to the operation of digital content without further set-up of the sensing environment. For designing this new system, we needed to answer the four design questions based on the QOC-based design space (Chapter 3).

For design question #1, I identified that it is important to recognize the linear translation and the rotation of a piece of paper, to use the position of the paper as control for the digital content. In addition, folding constructs paper to different shapes,

[2] Publication:

1. Kening Zhu; Fernando, O.N.N.; Theam Wei Yang; Cheok, A.D.; Fiala, M.; , "Origami recognition system using natural feature tracking," Mixed and Augmented Reality (ISMAR), 2010 9th IEEE International Symposium on , vol., no., pp.307, 13-16 Oct. 2010

which can be used as a metaphor for digital content. Since the main focus here is to develop a better algorithm for sensing movable paper craft, I decided to simplify the output of the movable paper craft as generating virtual content based on the shapes of the paper folding. Based on these assumptions, I provided the answers for design question #1 and question #2 as shown in Figure 4.1.

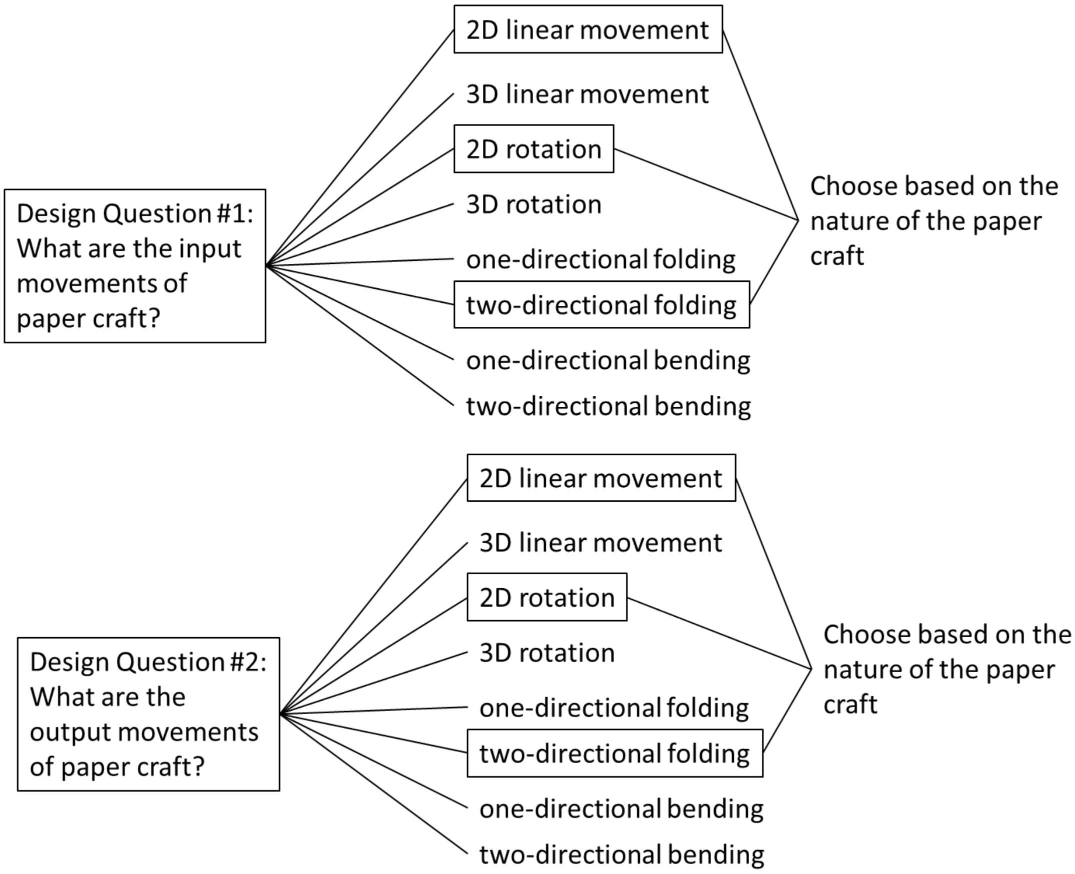
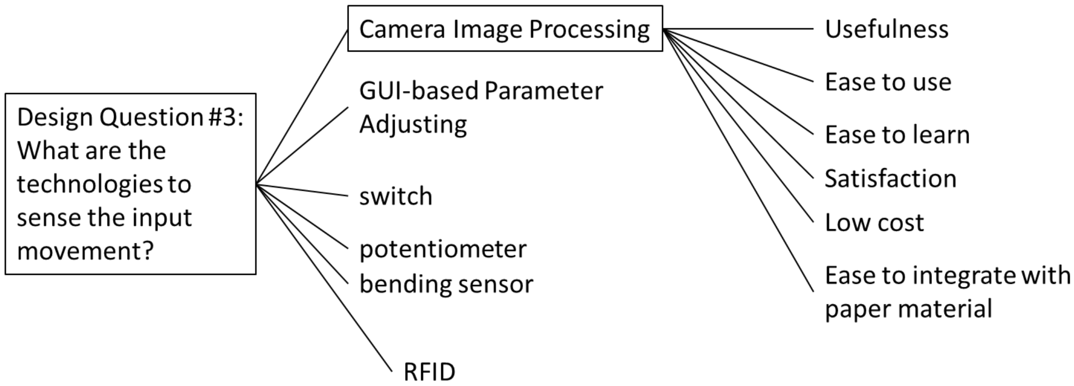


Figure 4.1: Answering design questions #1 & #2 for natural-feature-tracking-based origami recognition.

We would like to develop a new algorithm for sensing movable paper craft which is able to fulfill all the design criteria (Figure 4.2).



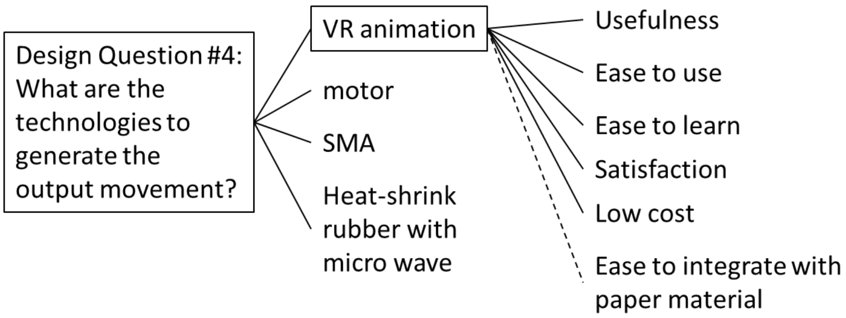


Figure 4.2: Answering design question #3 & #4 for natural-feature-tracking-based origami recognition.

Based on these design requirements, I developed a natural-feature-tracking-based algorithm for recognizing different patterns of origami (paper-folding), linear translation, and rotation using ordinary colored paper. To start, we decided to recognize five basic foldings for origami [100], as shown Figure 4.3, including book fold, kite fold, cupboard fold, shawl fold, and cushion fold.

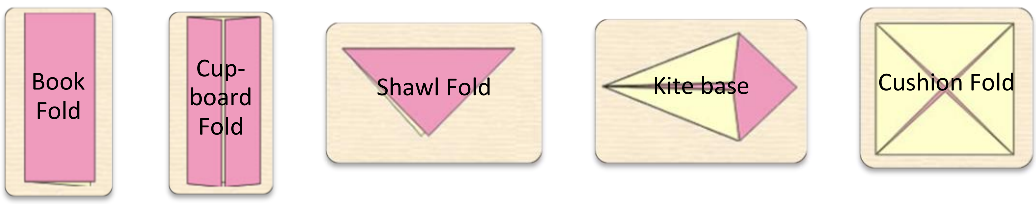


Figure 4.3: Five basic origami techniques

Many complex forms of origami can be derived from the five standard bases, as shown in Figure 4.4. Hence, these bases can be viewed as an introduction to origami, and their simplicity is suitable for beginners.

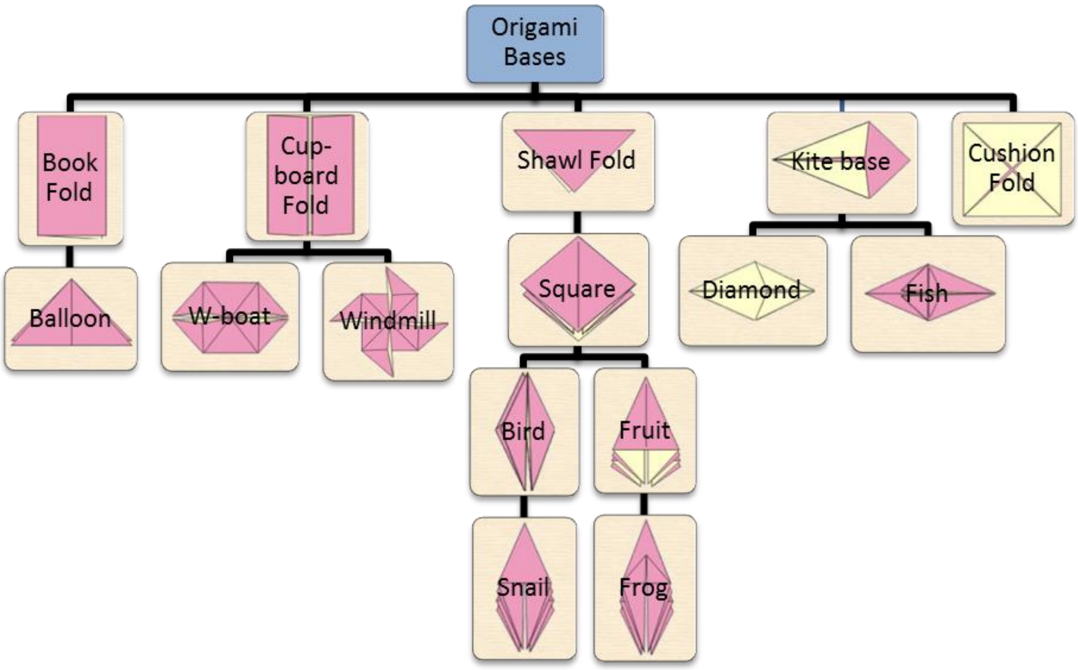


Figure 4.4: Tree structure of origami

Furthermore, these origami bases can be divided into folding steps. As illustrated in Figure 4.5, the cushion fold can be created using the folding in type 1, type 2, type 3, and type 4; the book fold can be created using type 5, type 6, type 7, or type 8; the shawl fold can be created with type 9, type 10, type 11, or type 12; the kite base can be created using the folding from type 13 to type 20; finally, the cupboard base can be created with type 21 and type 22 or type 23 and type 24. Therefore, this algorithm aimed to recognize all of these 24 types of different folding. The details of the algorithm will be presented in the rest of this chapter.

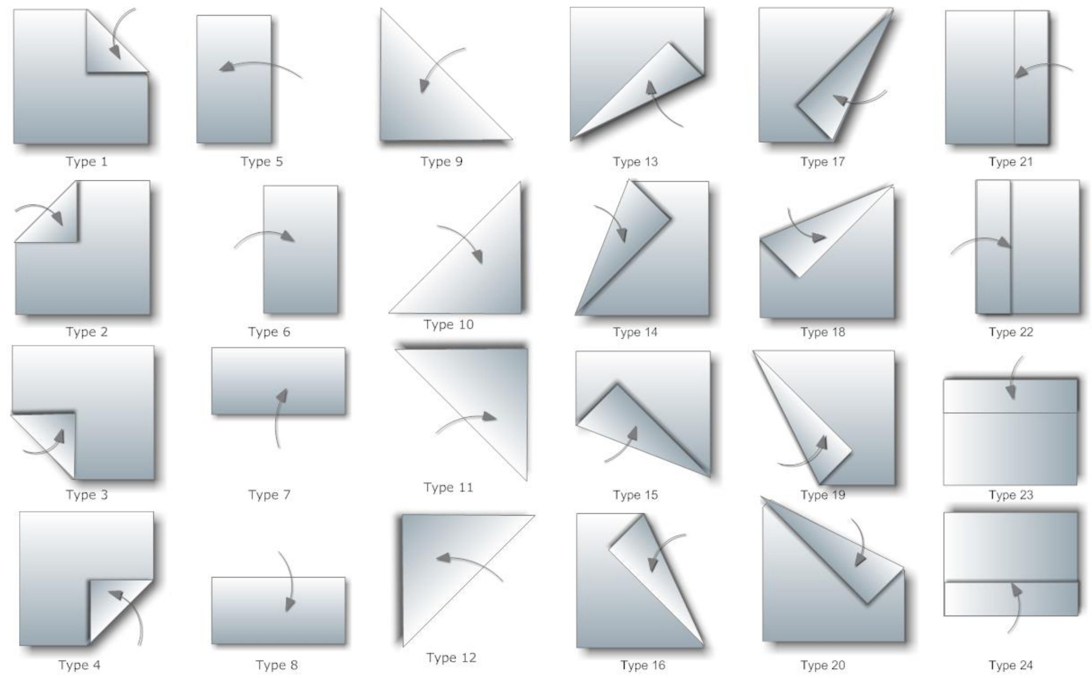


Figure 4.5: Possible steps of folding origami bases

4.2 Analysis with the Semantic Model

This new system of origami recognition can track linear movement, rotation, and folding in different directions of a piece of paper and affect digital information as an input method. Using the semantic model in Chapter 3, we can model it as below:

$$(Movement: Fold, Linear, Rotary, MovementStyle: Continous, R: \neg Bend | \neg Fold | 2DLinear | 2$$

In the design space (Table 4.1),**错误!未找到引用源。**, we can see that this algorithm covers the cells of 2D linear movement, 2D rotary movement, and multiple-direction folding and bending. This clearly shows that this algorithm is able to recognize more movement than the existing works. The same as in Table 3.1, the dashed line indicates the | (or) relationship between two movements and the arrow indicates the input-output relationship between movements.

Table 4.1: Analyzing Natural-feature-based Origami Recognition

Not Within Paper					Within Paper				
Rotary Motion		Linear Motion			Bend		Fold		
2D	3D	1D	2D	3D	Single Direction	Multiple Direction	Single Direction	Multiple Direction	
		③	③		③⑪ ⑤ ④	⑫	⑥ ⑤② ④	⑫	Binary
⑫			⑫		⑩		① ⑨	⑦⑧ ⑨	Continuous

①: Programmable Hinge [101]

②: Interactive Paper Devices [76]

③: Animated Paper [43]

④: Electronic Popables [71]

⑤: Animating Paper with SMA [70]

⑥: Pulp-based Computing [14]

⑦: Oribotics [26]

⑧: Adaptive Bloom [29]

⑨: Programmable matter by folding [31]

⑩: Popapy [102]

⑪: Move-it [69]

⑫: Natural-feature-based Origami Recognition

4.3 Algorithm Overview

The whole origami interaction system consists of two main modules: paper registration and folding recognition, which are built on top of Speeded Up Robust

Feature (SURF) algorithm [33]. As shown in Figure 4.6, users place a square piece of his/her desired paper under the camera that is set on top of the table. The paper registration module analyses the paper and extracts the natural feature points on the paper based on SURF descriptors. In this step, the system reports to the user whether there are sufficient features to utilize for tracking. Therefore, users should supply sufficiently-textured paper to the system in this step. The feature points will also be used in the step of origami recognition, where SURF is used to track the visibility of different regions of the origami paper to recognize different types of folding performed by the users. The rest of this section will explain why we chose SURF as our fundamental algorithm and then discuss the features of our method in details.

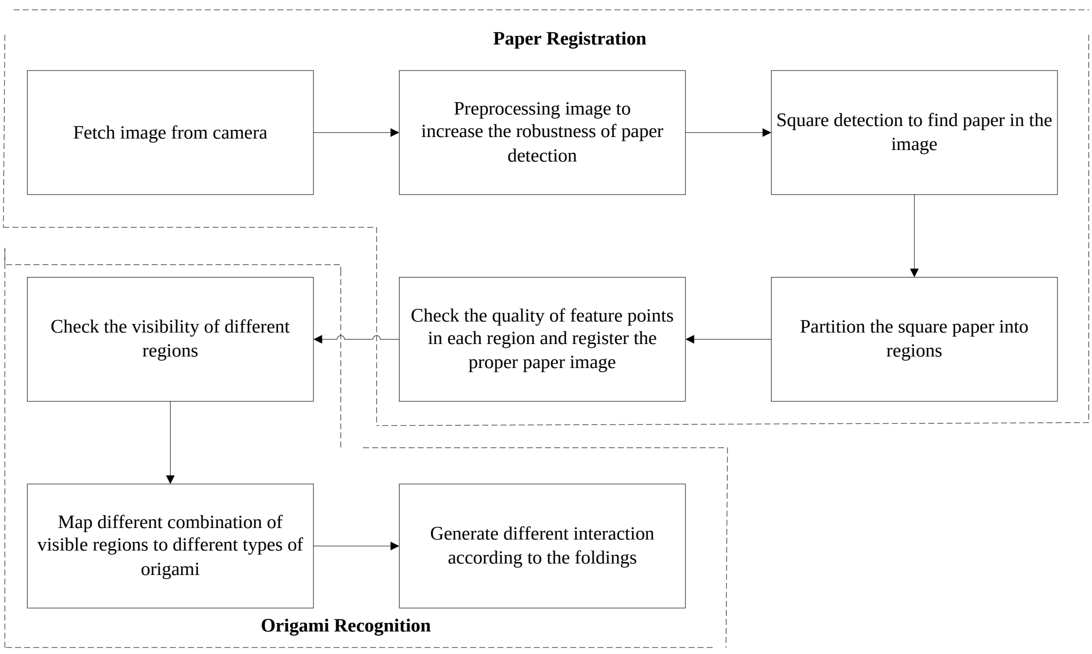


Figure 4.6: Overview of the algorithm flow

4.4 Experiment on Algorithm Selection

Based on a series of image training and experiments done on different types of detectors and descriptors, SURF with Fast Hessian detector [33] was selected as the natural-feature-tracking algorithm for our origami recognition system. As shown in

Figure 4.7, we performed the matching of four different types of origami paper with simple folding using the SURF algorithm. The results show that SURF could provide good feature tracking even with the presence of human hands. Another main reason it was chosen is that SURF descriptor requires less computational time compared to others, resulting in faster tracking of objects. Although SIFT [52] is more robust in term of correct matching, affine distortion, and illumination changes, our origami recognition system uses only static camera and nearly constant lightning condition, which gives less distortion and fewer illumination changes.

(a) (b)

Figure 4.7: Test of Different Paper Tracking using SURF: (a) postcard, (b) newspaper

As the SURF algorithm consists of three main parameters: Fast-Hessian threshold, number of octaves, and number of layers, it is necessary to obtain the optimum values that fulfill the requirement of efficiency and correctness in the origami recognition system. Figure 4.8 shows the testing image used for the experiment.

Figure 4.8: Testing Image for SURF Parameter Selection

As shown in Figure 4.9, with the increase of feature points and the robustness, the computation time is increased in the SURF processing. Since the origami recognition system only performs detection every 1000 milliseconds, the highest number of interest points with acceptable long computational time is selected.

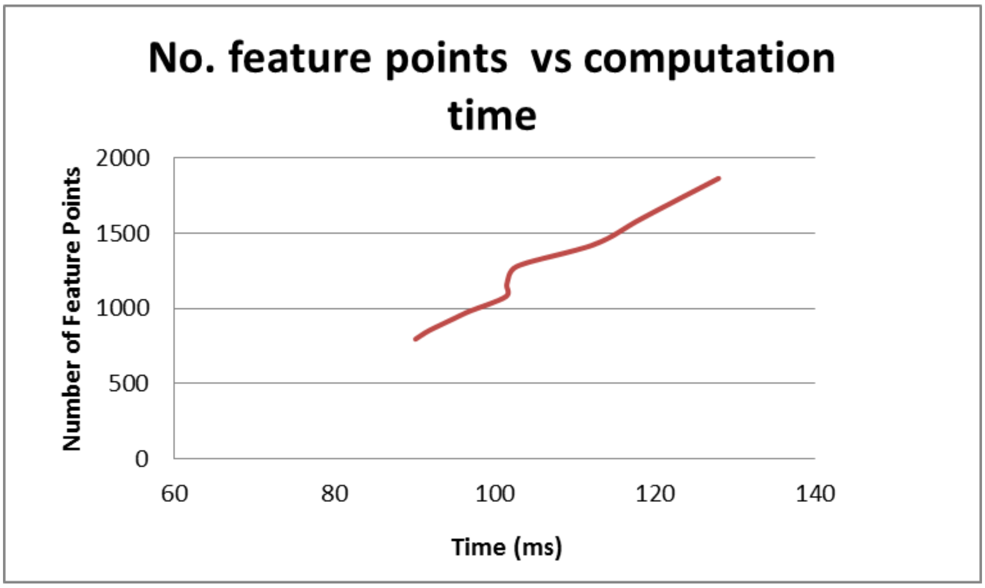


Figure 4.9: The relation of number of feature points and computational time

After experimenting with different combinations of the three main parameters in SURF as shown in Figure 4.10, Figure 4.11 and Figure 4.12, I decided the values as Fast Hessian threshold = 100, Number of octaves = 5 and Number of layers = 4. In addition, the 128-element descriptor was chosen.

Figure 4.10: The relation of number of feature points and Fast-Hessian threshold

Figure 4.11: The relation of number of feature points and number of octave

Figure 4.12: The relation of number of feature points and number of layer in SURF

4.5 Detailed Description of the Algorithm

4.5.1 Square Paper Detection

Since the most common origami paper is approximately in a square shape, our system performs a process of square detection, as shown in Figure 4.13, when the user places his/her origami paper under the camera in the beginning.

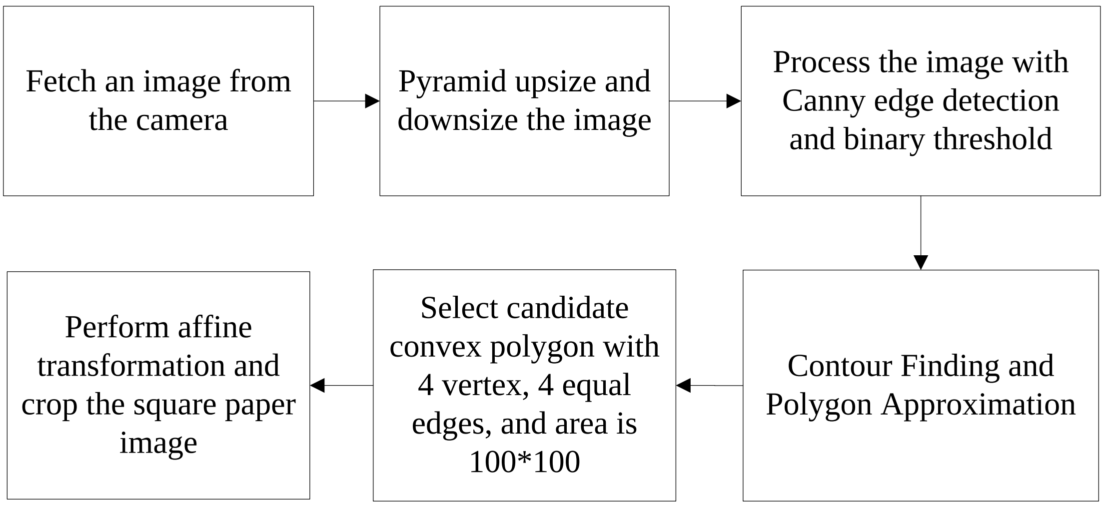


Figure 4.13: Flowchart of square paper detection

Firstly, to reduce noise and peak intensity in pixels, image smoothing is executed by using pyramid downsize and upsize of the image captured by the camera. Here a 5x5 Gaussian kernel, as shown in the equation below, is used for the smoothing.

$$5x5-Gaussian-kernel=1/16*\begin{pmatrix}1&4&6&4&1\\4&16&24&16&1\\6&24&36&24&6\\4&16&24&16&1\\1&4&6&4&1\end{pmatrix}$$

After smoothing, Canny edge detection [11] and image dilation are performed with a 3x3 rectangular structuring element, and potential holes between edge segments from Canny detection are removed. Then different levels of binary threshold setting are done in each of the three color channels to search possible polygons in different channels, as shown in Figure 4.14.

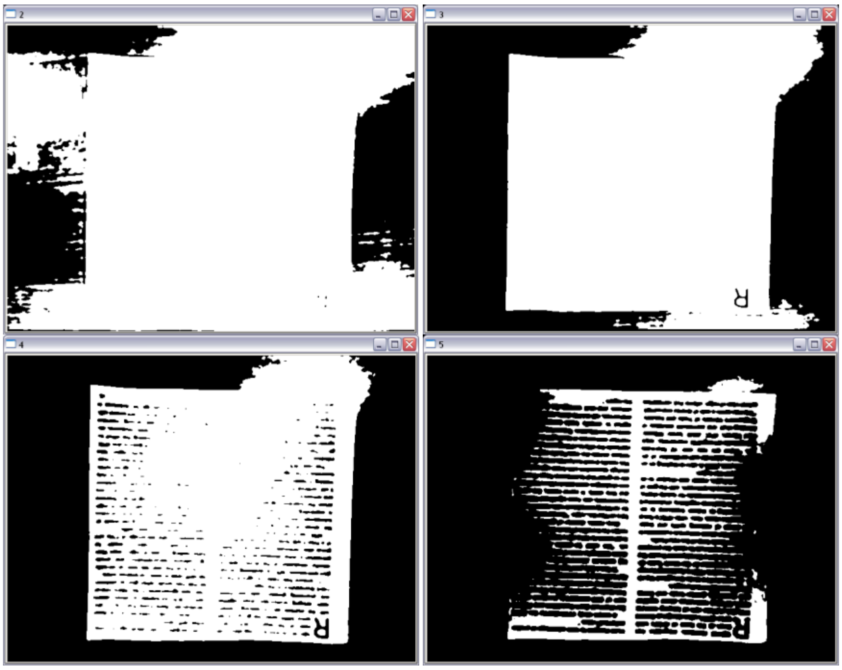


Figure 4.14: Binary result of paper image

Finally, a series of filters are set to obtain the proper square. The possible candidates have to first pass through a corner angle test that requires the angle to be approximately 90 degrees and an edge length test that requires 4 edges be approximately equal in length. The final filter for the square detection is to remove the adjacent squares which are only five pixels deviated from others. The main purpose of this final filter is to remove squares overlapping in similar locations which result from image smoothing and dilation. After the filtering, rotation and cropping of the image are executed due to the requirement of exact coordinates of feature points during the origami recognition. The final result of origami paper detection is shown in Figure 4.15. This process is performed for both the front side and back side of the paper.

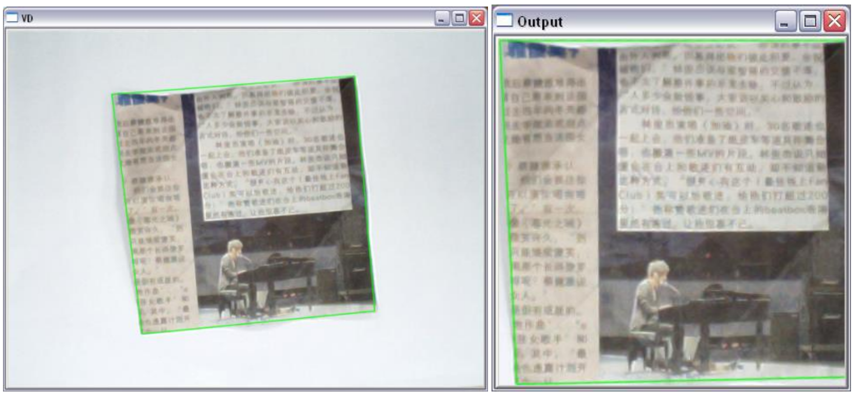


Figure 4.15: Result of square paper detection

4.5.2 SURF-based Paper Analysis

The images of the square paper are passed to the module of SURF-based paper analysis, shown in Figure 4.16, which determines whether the paper is textured enough for camera tracking and then extracts the necessary feature points for origami recognition.

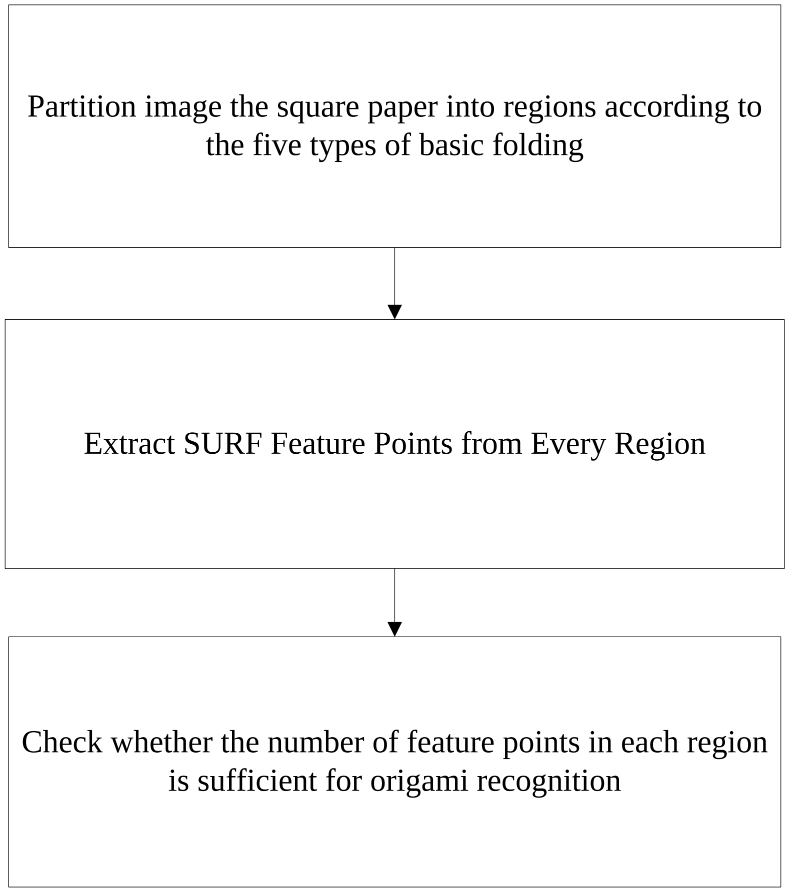


Figure 4.16: Flow Chart of SURF-based paper analysis

Based on the five basic types of origami folding, the system first divides both the front square and the back square into regions as shown in Figure 4.17. These regions are defined mathematically using the combination of the equations of straight lines. Then the regions will be checked one by one for the sufficient number of feature points.

The division straight lines, in Figure 4.17, will be defined in equations as follows:

Given that w = the width of image and h = the height of the image, define a = 0.4142 and b = 0.5858, and x_i and y_i are the coordinates horizontally and vertically with the center of the paper as the original point.

Front side line equation for 6 straight lines:

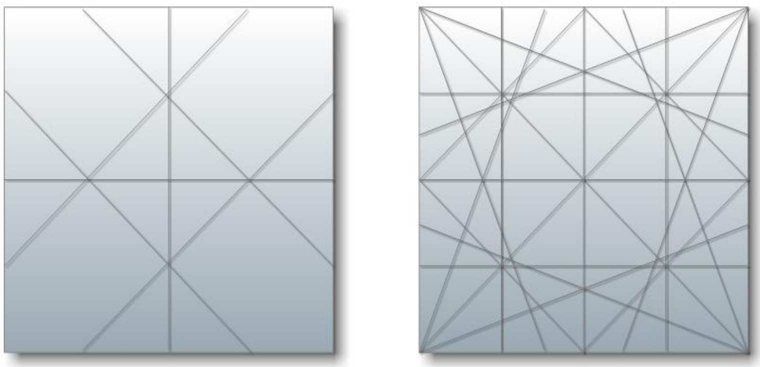
$$x_i = \begin{cases} \frac{w}{2} & y = 0 \\ \frac{(y_i - hb_i)w}{m_i h} & otherwise \end{cases} \quad i = 1 \ldots 6$$

$$m_i = \begin{bmatrix} 0 & -1 & 1 & -1 & 1 \end{bmatrix}$$
$$b_i = \begin{bmatrix} 0 & 1+\alpha & \alpha & \beta & -\alpha \end{bmatrix}$$

Back side line equation for 20 straight lines:

$$\begin{cases} x_j = \frac{w}{4}, \frac{2w}{4}, \frac{3w}{4} & y = 0 \\ y_j = \frac{h}{4}, \frac{2h}{4}, \frac{3h}{4} & x = 0 \\ y_j = m_j \frac{h}{w} x_j + b_i h & x \neq 0, y \neq 0 \end{cases} \quad j = 1 \ldots 20$$

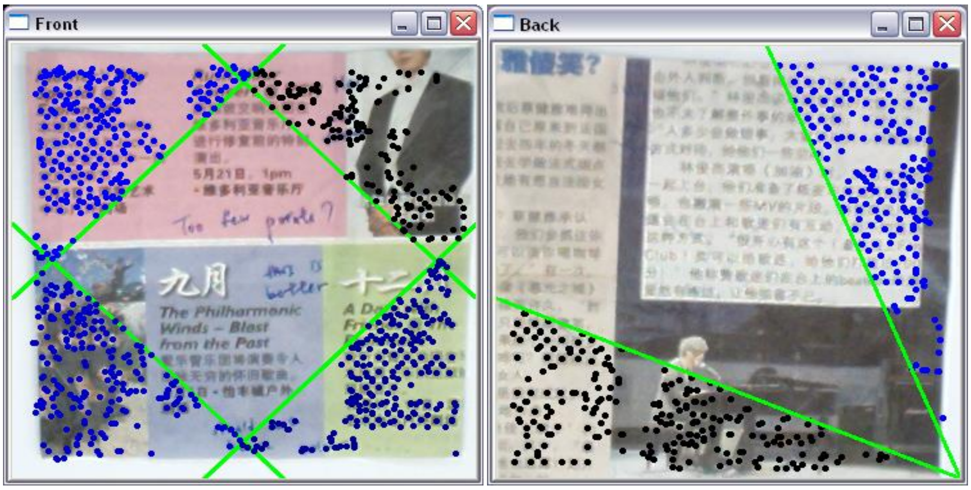
$$m_j = \begin{bmatrix} -1 & 1 & -1 & 1 & 1 & -1 & -\alpha \\ (-\frac{1}{\alpha}) & \alpha & (\frac{1}{\alpha}) & (-\frac{1}{\alpha}) & -\alpha & (\frac{1}{\alpha}) & \alpha \end{bmatrix}$$
$$b_j = \begin{bmatrix} \frac{3}{2} & \frac{1}{2} & \frac{1}{2} & -\frac{1}{2} & 0 & 1 & \alpha \\ \frac{1}{\alpha} & 0 & 0 & 1 & 1 & -(1+\alpha) & \beta \end{bmatrix}$$



(a) (b)

Figure 4.17: Partition of Paper: (a) front partition (b) back partition

The procedure of the paper analysis is based on the SURF algorithm. With the proper parameters, the system will check every region in the square paper based on a set of criteria, such as the total number of feature points and the density and distribution of the feature points in a particular region. Figure 4.18 shows the results of feature points in the front and back of the origami.



(a) (b)

Figure 4.18: Feature points checking in different regions of the paper: (a) front image, (b) back image

After this analysis, the system will report to the user whether his/her current origami paper is textured enough for the origami tracking interaction. The system will register the final well-textured paper for the origami recognition module.

4.5.3 Origami Recognition

In the module of origami recognition, as shown in Figure 4.19, based on the SURF matching method, the paper image in each frame is compared with the square images of the square images stored by the previous steps.

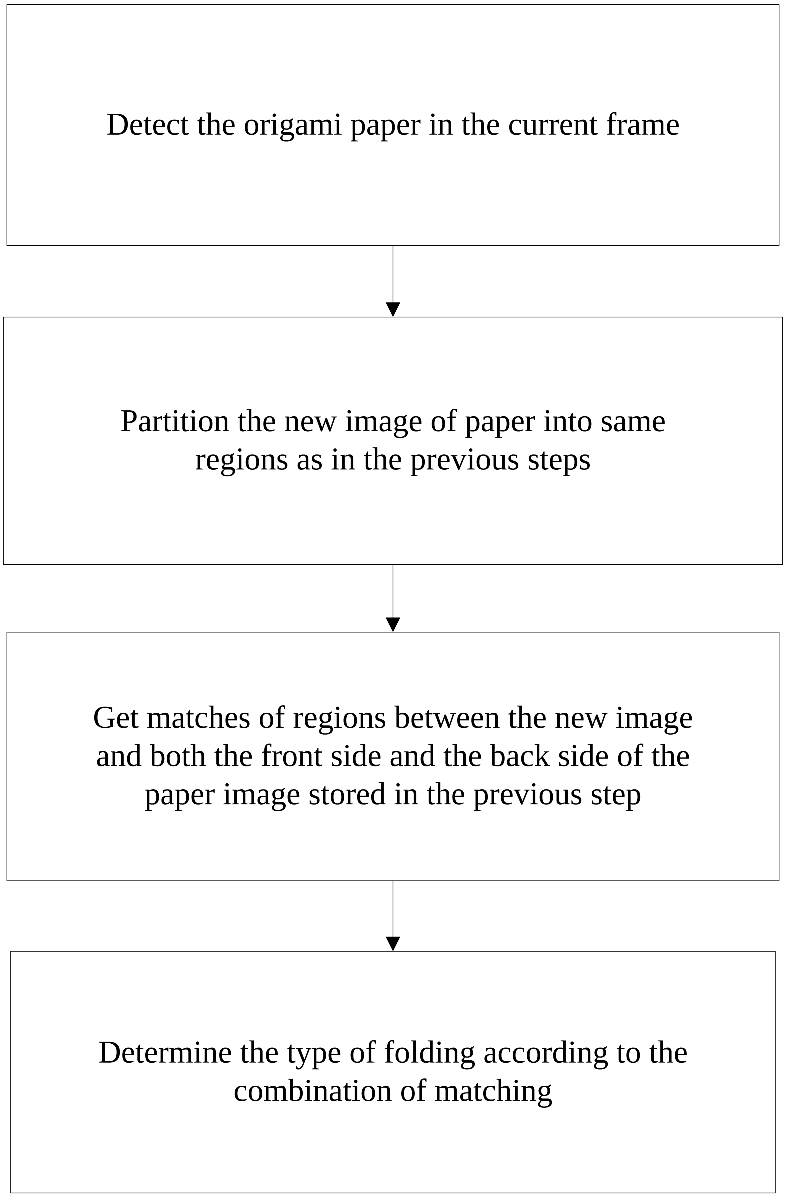


Figure 4.19: Flowchart of origami recognition

I decided 1000 milliseconds is an acceptable update rate for origami. This allows us to use more interest points, and a full 128-element description was chosen for the matching between the paper image captured real time and the pre-stored template images of the paper.

With the proper parameters, the tracking algorithm recognizes different types of origami folding according to the visibility of the feature points in each region in the paper. The regions represented in the front side and back side of the origami paper are different because most folding types cover the entire front side of the paper. Before determining the appearance of a particular region, the threshold for each region has to be calculated. The threshold refers to the number of feature points so that when detected points are higher than this threshold, the particular region is considered shown and not blocked. As the total number of feature points for different origami paper is not the same, a dynamic threshold has to be implemented in order to determine the appearance of a particular region. Different types of folding are mapped to different combinations of the appearance of regions. For example, the disappearance of the top right corner of the front side and the appearance of the top left corner of the back side can be recognized as the folding shown in Figure 4.20. Finally, the system can recognize 24 types of simple folding as shown in Figure 4.5.

Figure 4.20: Result of folding detection

4.5.4 Application: Origami Tower

This origami recognition system provides a platform for a wide range of applications in education, entertainment and social communication, including storytelling, gaming, designing, etc. As a proof of concept, a flash game application called Origami Tower was developed to realize this origami recognition method. As shown in Figure 4.21, the main objective of the game is to construct towers to defeat virtual monsters. The towers in the game are represented uniquely by different kinds of fundamental origami folding. Hence, in order to win the game, players are required to construct one or more origami basic foldings to build defending towers.

In addition, this game application also presents a way to replace or substitute keyboard, mouse, or joystick as an input to the computer. This game only requires one paper from the user, and then he/she can navigate the virtual world using the origami paper. For instance, by constructing the arrow shape pointing upwards, which is shown in Figure 4.21, the navigation box will move to the up direction accordingly.

Figure 4.21: Origami-based Interactive Gaming: user performs basic folding to create objects in the gaming environment

During the interaction, a real-time video is streamed and shown in the flash game. The origami recognition algorithm is running in the background and is providing real-time update to the gaming interaction. Thirty frames per second are achieved by using a video frame splitter. As each folding requires some time to complete, it is unnecessary to waste resources to do the folding recognition every frame. Hence, the video frame is split and one of them is used for updating the screen for real-time streaming and another is used for detecting folding for every 1 second, which is approximately 30 frames apart. Although this may result in some delay for the folding recognition, it is hard for users to notice in this small interval of time according to our primitive observation.

4.6 User Experience on Origami Tower

In order to further study its fulfillment of the design criteria for TEMPC, we set up the Origami Tower game in a lab environment as shown in Figure 4.22 and invited paper-craft hobbyists for the experiments.

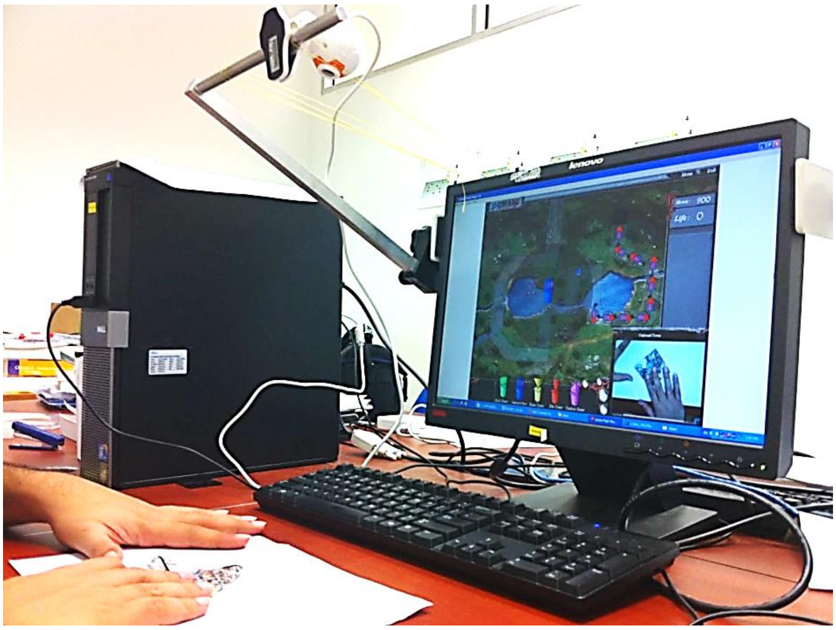


Figure 4.22: Set up of Origami Tower user test.

We invited 20 paper-craft hobbyists to use the prototype of Origami Tower and studied the experience of playing games with origami. The users' ages ranged from 20 to 55 years (M=30, SD=4.52). During the registration for this user study, we collected information on each user's background skills in paper craft. The detailed distribution of the participants' backgrounds is shown in Figure 4.23.

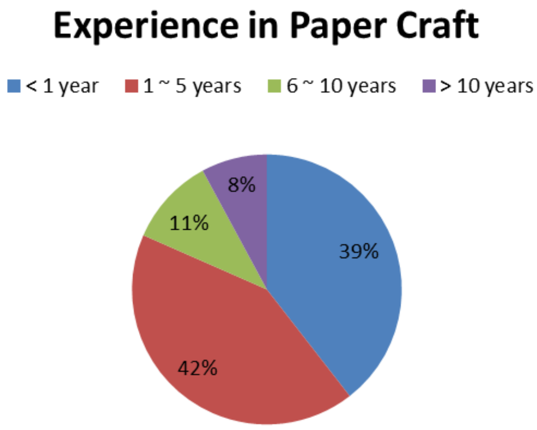


Figure 4.23: Users' experience in paper craft.

Due to the limit of resources, only one user participated in the study at a time, and one whole user study lasted 1 hour. First, the study facilitator spent around 15 minutes introducing the game play of Origami Tower and demonstrating the process of registering paper and using paper to control the game play, including in-game navigation and object building. After this introductory session, the user had a 15-minute session to play around freely with the Origami Tower system. The user was allowed to bring his/her origami paper and register the paper with the system and test the game play with origami. Finally, the user was asked to perform the game play for 30 minutes to win the game by constructing as many virtual towers as possible and defeating the virtual monsters by using origami. After the game-play session, the user completed a questionnaire for rating his/her experience, including comments on the origami-based game play.

The questionnaire for using Origami Tower, as shown in Appendix B, was designed based on the design criteria for TEMPC. Therefore, the results of this study are categorized based on the design criteria, as described in the following. The quantitative details of the study on using Origami Tower are shown in Appendix C.

- Ease to Learn

All of the users found that the introduction session was clear to follow and that it was easy for them to understand how to use Origami Tower. The factor of ease to learn was proved by the score of 4.3/5 for the statement of *The tutorial is clear for me to learn how to play the game,* and the score of 4.7/5 for the statement of *It is easy for me to be familiar with playing the game with origami.*

- Ease to Use

Most of the users agreed that it is easy for them to use paper to navigate in the game and construct virtual towers, and that they do not need to worry about their hands blocking the paper. A user just used the newspaper and played the game. However, some of them commented that it would be difficult to set up the top-view camera by themselves, since the set-up of the user study required a metal frame to mount the camera. We argue that this is the main drawback of camera-image-processing-based technology, as it requires the camera to be set up at a particular angle for capturing the origami images. Therefore, this shortcoming affects the ease of integrating with paper craft in the Origami Tower. The score for the statement *It is easy to use paper to move in the game* is 4.3/5, and the statement *It is easy to fold the paper and build a tower in the game* scored 4.1/5, while the statement *It is easy to set up the game in my own place* had a lower score, 2.7/5.

- Usefulness & Low cost

All of the users mentioned that the algorithm in this game worked well while playing Origami Tower, and there was no system crash during all the user studies. In terms of the cost of the system, all the users were willing to pay for the game.

- Satisfaction

Users commented that it was more fun to play the game with origami than traditionally with mouse and keyboard, and that they would like to see more and more games that could be controlled by physical paper craft. One user mentioned, "I have this imagination, when I was a kid, that I can see my paper craft become alive somehow, and now I could create objects in game using origami, it is somehow like my dream." However, users also mentioned that they prefer more tangible output, such as physical movement of the paper craft instead of VR animation. The statements on user satisfaction all scored high on the average of 4.3/5.

4.7 Summary

In this chapter, I presented a new algorithm of recognizing movable paper craft based on natural-feature tracking. This algorithm was designed based on the QOC-based design space for TEMPC. It is further development on top of the SURF algorithm with proper parameters which meet the requirement of a sufficient real-time recognition for movable paper craft, including origami, rotation, and linear translation. A simple game application was developed to assess the robustness and responsiveness of our system. The results of the user study of the game prototype showed that the algorithm and the prototype fulfill the design criteria in the design space. The study further suggested that users enjoyed using paper, especially old newspaper or waste paper, as the medium for the system. However, the system requires setting up special angles of the camera for most methods in camera image processing, and this drawback affected the user experience in Origami Tower. In addition, the study provided important insight that users prefer more tangible controllability than just watching VR animation.

This chapter demonstrated the capability of using the design space to design new algorithms and systems for sensing movable paper craft as input to digital content. Generating movable paper craft as output is the equally important half of TEMPC; therefore I explored the aspect of outputting TEMPC by developing an origami generation system called Snap-n-Fold, whose details will be presented in Chapter 5. The user study of the system reflected the main drawbacks of the system and provided valuable lessons for me in developing new technologies for TEMPC.

Chapter 5 Generating Paper craft as Output[3]

Following the new system for recognizing movable paper craft as input in Chapter 4, Chapter 5 focuses on a software-based system that generates paper-folding patterns based on the image of real-life objects, to further explore the taxonomy of TEMPC. As most interests have been focused on sensing paper craft movement, especially in understanding the process of origami (paper folding) using the technologies of computer vision and image processing, there are no equivalent efforts in the aspect of generating paper-craft movement automatically. In this chapter, I introduce a new technique for generating automated paper movements. Snap-n-Fold is an origami-generating system based on the structure of real-life objects captured by the camera. It is based on an algorithm combining object extraction, structure skeletonization, and origami generation. The user study of Snap-n-Fold suggested it could not fulfill the design criteria well, especially for users with little experience in origami, but valuable lessons on designing TEMPC systems were learned during the user study.

5.1 Motivation

In the early days of origami, development of new designs was largely a mix of trial-and-error, luck and serendipity. Later on, Robert J. Lang et al. [46] developed origami mathematics which allows for the creation of extremely complex multi-limbed models, such as many-legged centipedes, human figures with a full complement of fingers and toes, and the like. Origami artists can then follow this method to create their own crease patterns without the boring procedure of trial-and-error. However, the method of origami mathematics is not suitable for ordinary users who have no professional

[3] Publication:

1. Kening Zhu, Chamika Deshan, and Owen Noel Newton Fernando. 2012. Snap-n-fold: origami pattern generation based real-life object structure. In Proceedings of the 2012 ACM annual conference extended abstracts on Human Factors in Computing Systems Extended Abstracts (CHI EA '12 Work in Progress). ACM, New York, NY, USA, 2345-2350.

experience in paper-folding. It is difficult for them to design a complex origami pattern as mentioned before. There are only a few researches and development focused on facilitating users' origami pattern designing. The most famous software for origami design is TreeMaker by Robert J. Lang [47]. In TreeMaker, users draw a stick structure of the object on the screen, where each drawing in the stick structure will be represented by a flap on the base. Once the structure is defined, the program generates the full crease pattern for a base which, when folded, will have a projection equivalent to that specified by the defining object. As a result, users can print out the crease pattern and make the origami of the defined object. Another origami designing software is Doodle [30]. A unique descriptive language was designed in Doodle to produce origami diagrams. It allows a purely geometrical description of folding: each point is located in relation to the others in a precise and geometrical way. Each step is a succession of operators making it possible to calculate control points or to describe the movements to carry out the step using these points. However, it is still difficult for end-users to use Doodle because it requires geometric knowledge. This motivated me to develop Snap-n-Fold to facilitate users to design their own origami by just selecting real-life objects through camera snapping.

5.2 The Design of Snap-n-Fold

QOC-based design space helps us to generate the initial design requirement for designing the Snap-n-Fold.

Design Questions #1 & #3:

As shown in Figure 5.1, we would like to allow users to create an origami pattern based on the real-life object in which they are interested. Therefore, the input of Snap-n-Fold here would not be any movement of the paper but the photo image of a real-life object, so the technology will be based on camera image processing.

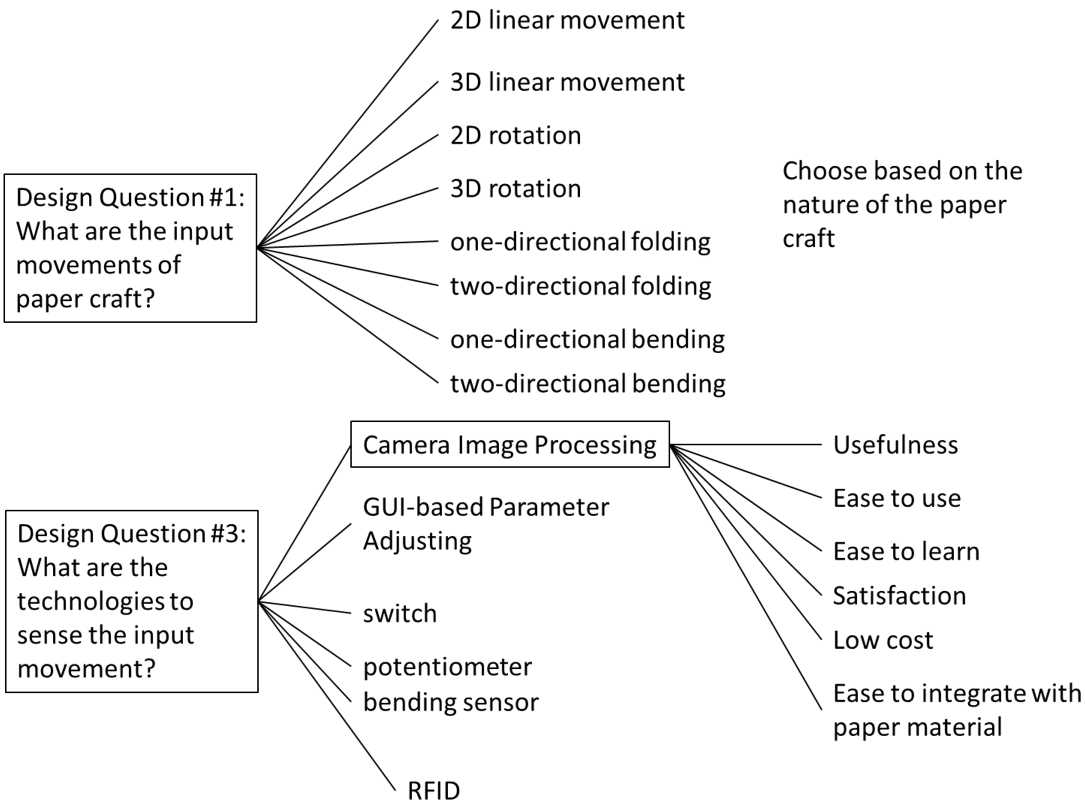


Figure 5.1: Design questions #1 and #3 for Snap-n-Fold

Design Questions #2 & #4:

A virtual-reality animation would need to be generated along the origami pattern to teach users how to fold step-by-step. Therefore, we will generate the output movement by using VR simulation (Figure 5.2).

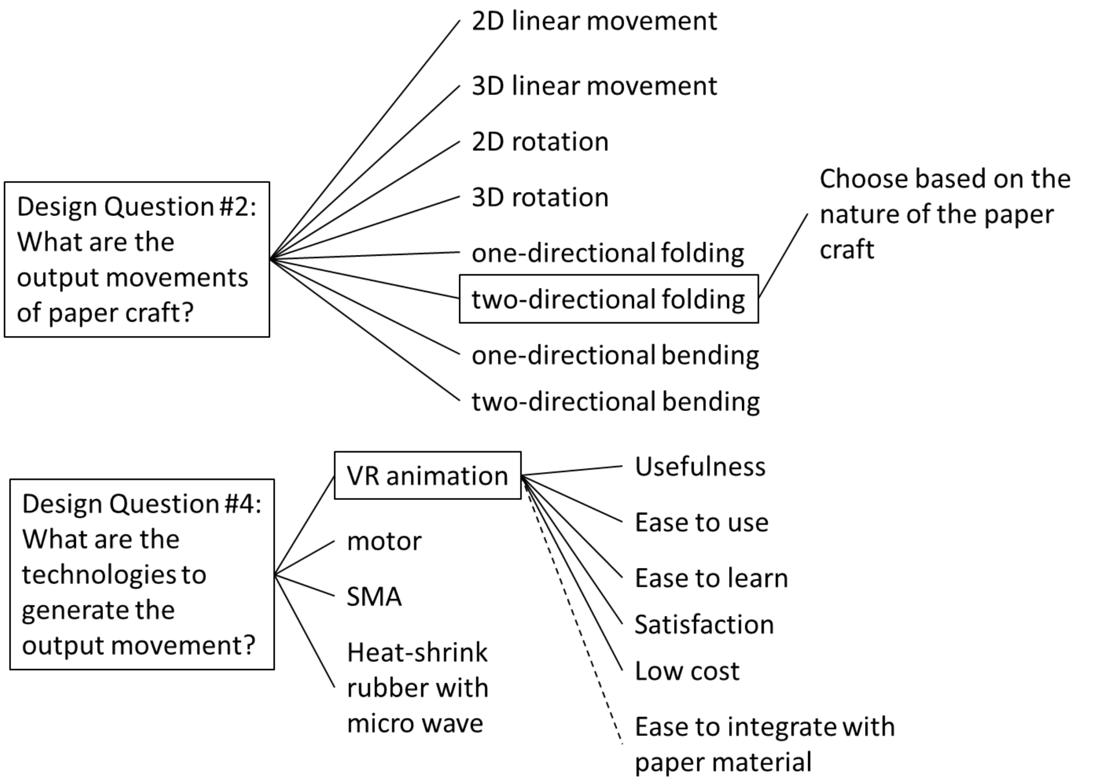


Figure 5.2: Design questions #2 and #4 for Snap-n-Fold.

5.2.1 System Overview

There are three main steps in the process of real-object-based origami generation in Snap-n-Fold: selected object extraction, object skeletonization, and origami pattern generation. In addition, as the first prototype, the system requires users to select the real-life object with simple interaction: pointing the camera to the real-life object and dragging the rectangle box for the object selection.

As shown in Figure 5.3, the system first extracts the selected object from the image background according to the difference between the color signatures of both the selected object and the other part of the image. Then a thinning algorithm [28] is performed to generate the skeleton structure of the object which is converted to the compatible tree format for the algorithm of origami generation in the next step. Finally, we integrated the algorithm of crease pattern generation developed by Robert J. Lang [46] in the Snap-n-Fold system. The algorithm receives the tree structure of the object's skeleton and generates the crease pattern of the origami base accordingly. The following sub-sections (5.2.2, 5.2.3, and 5.2.4) will describe the algorithm in detail, and Section 5.2.5 will provide an example of the results of the algorithm.

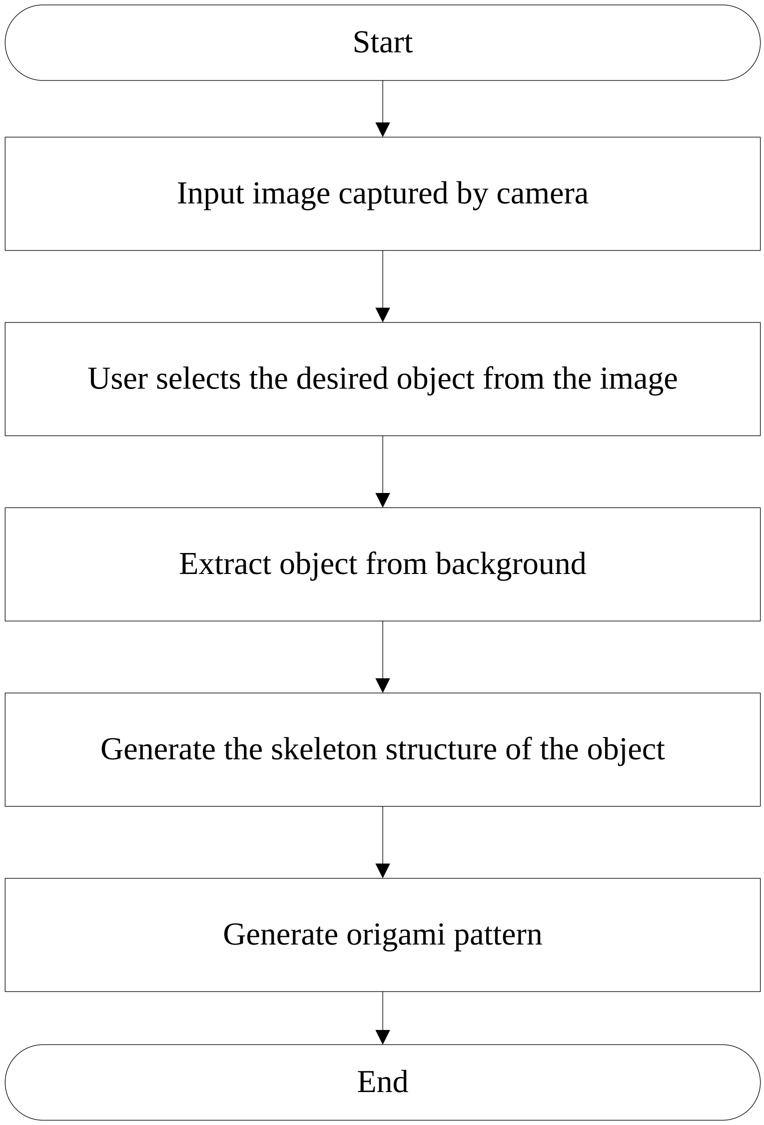


Figure 5.3: Overall procedure of Snap-n-Fold

5.2.2 Object Detection

The flowchart of object selection is shown in Figure 5.4. Given an input image with the foreground object selected by the user, the Snap-n-Fold system first performs an object-extraction method to acquire the selected object. There has been little research [6, 62, 73] focused on static object extraction from 2D image, most of which require a user's simple selection to achieve reasonable results. In Snap-n-Fold, a similar approach as GrabCut [73] is adopted since the implementation of this algorithm is available in the latest version of OpenCV. GrabCut is a process of automatic segmentation that builds a connective graph structure where each pixel is a node with edges to its 8 pixel neighbors, and the edges are weighted for a max-flow/min-cut problem solving.

Users select the object from an image by dragging the rectangle box. The system automatically extracts the selected object according to the color distribution of the image. In the following step, the system performs the algorithm of Otsu thresholding [68], a Canny edge detection [11] to attain both the shape and edge of the object. This shape image and edge image are passed to the next step of object skeletonization.

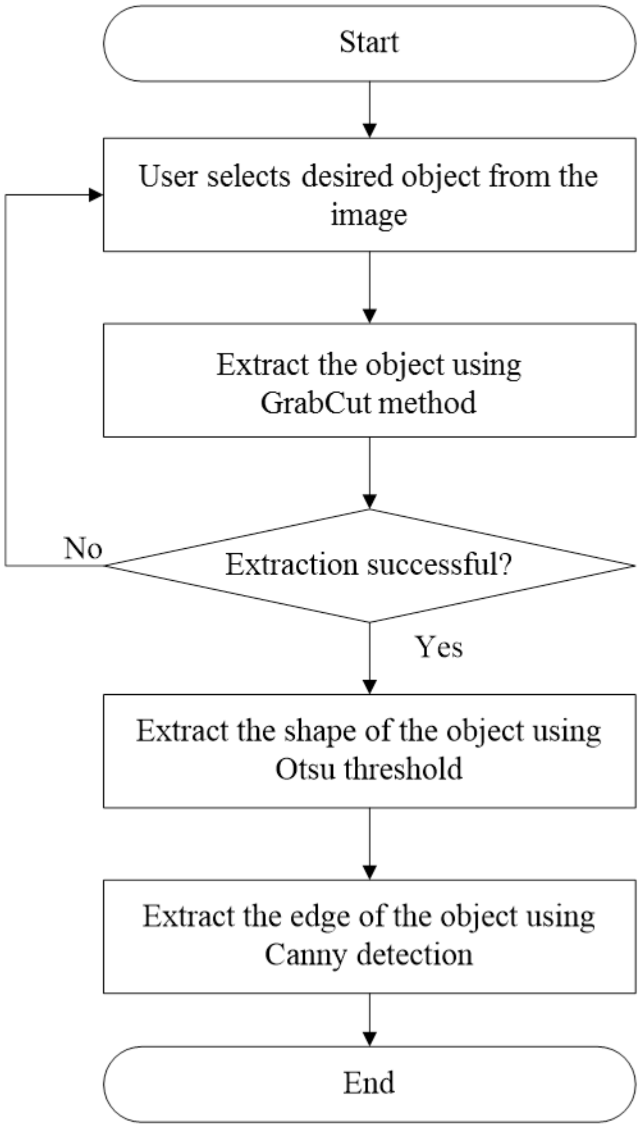


Figure 5.4: Flowchart of Object Selection in Snap-n-Fold

5.2.3 Object Skeletonization

The images of both shape and edge of the selected object are further analyzed to attain the object's skeleton structure for the final origami generation. This process consists of two steps: firstly converting the binary image of the object's shape into the basic structure of skeleton in the form of 1-pixel wide lines, and then generating the skeleton tree to represent the data structure of the skeleton which can be analyzed in the final step of origami generation.

In the step of basic skeletonization, the system applies a modified method based on the iterative thinning algorithm in [28]. Two conditions are defined as follow to delete unnecessary pixels:

- Condition 1

$(a) 2 \leq N(p_i) \leq 6$

$(b) T(p_i) = 1$

$(c) p_2 \cdot p_4 \cdot p_6 = 0$

$(d) p_4 \cdot p_6 \cdot p_8 = 0$

- Condition 2

$(a) 2 \leq N(p_i) \leq 6$

$(b) T(p_i) = 1$

$(c) p_2 \cdot p_4 \cdot p_8 = 0$

$(d) p_4 \cdot p_6 \cdot p_8 = 0$

Here, N(pi) is the number of non-zero neighbors of the pixel pi, and T(pi) is the times of 0 to 1 (or 1 to 0) transitions in the sequence of clockwise starting from p2 as shown in Figure 5.5.

p_9	p_2	p_3
p_8	p_1	p_4
p_7	p_6	p_5

Figure 5.5: 8-pixel neighbors in the thinning algorithm

Therefore, as the first step of object skeletonization, the thinning algorithm is performed iteratively as below. For the final result image of thinning, the system marks every remaining pixel with white color and the background with black.

Shape Thinning and Skeleton in Snap-n-Fold

1. I1 := Binary-thresholding image of the selected object;
2. I2 := Edge image of I1;
3. FOR P1: = every pixel in I2
   IF P1 satisfies Condition1 in I1
   Mark P1;
4. Delete all the marked pixels in I1 and generate new image I1';
5. I2' := Edged image of I1';
6. FOR P1' := every pixel in I2'
   IF P1' satisfies Condition2 in I1'
   Mark P1';
7. Delete all the marked pixels in I1' and generate new image;
8. Repeat Step 1 until no pixel can be deleted;
9. Get final skeleton S;
10. Extract the set of end-points E{} and the set of branch point B{} from S;
11. Build the connectivity table T.

With the result of the basic thinning algorithm, Snap-n-Fold further analyses and creates the data structure of the skeleton tree for the selected object. Before explaining the method of building the data structure for an object's skeleton, we will establish two definitions:

End-point is a point that has only one edge connected to it.

Branch-point is a point that has more than two edges connected to it.

Firstly, every end-point and every branch-point are identified separately in the thinned shape by analyzing the 8 neighboring pixels of each pixel. The pixel with only one white neighboring pixel is classified as end-point, while the pixel with more than two white neighbors meets the criteria of a branch-point.

Then, a Boolean table is created for representing the direct connectivity of each *end-point* or *branch-point* as shown in Table 5.1: Boolean Table for Direct Connectivity. Here Bp means branch-point, Ep means end-point, and the value of the unit is 1 if two points are directly connected, otherwise the value is 0.. We can then define the value of one cell in

Table 5.1, $[Bp_n, Bp_m]$ as the connectivity between two points,

where Bp_n means the row number of the table, and Bp_m means the column number of the table. When the value of $[Bp_n, Bp_m]$ is 1, Point p_n and Point p_m are connected. When the value of $[Bp_n, Bp_m]$ is 0, Point p_n and Point p_m are not connected.

By tracing the edge among the connection of each end-point, the first found branch-point is directly connected to this end-point. Similarly, the directly-connected branch-points can be found for each branch-point by iteratively tracing along the direction of each connected neighboring pixel.

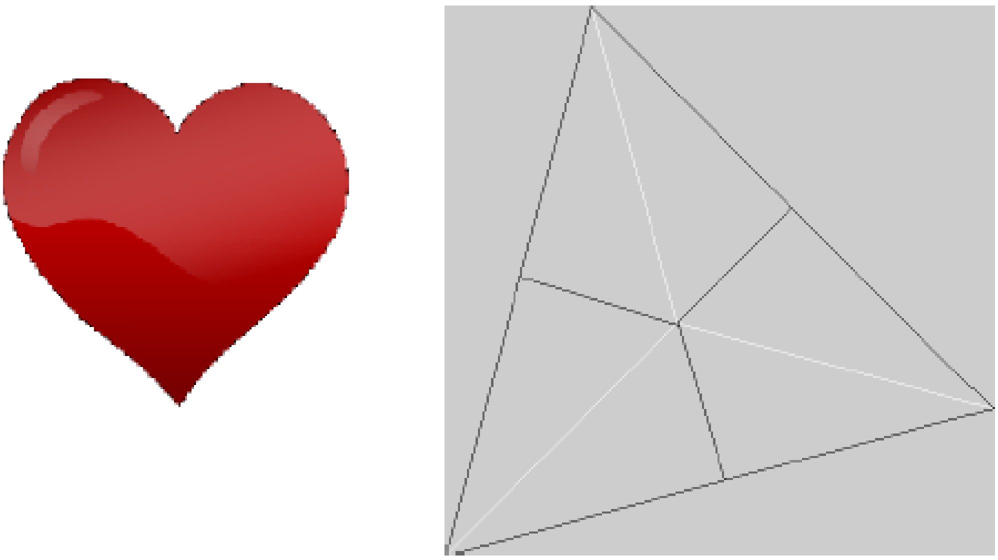
Finally, the connectivity table will be passed to further analysis of the final origami pattern generation.

Table 5.1: Boolean Table for Direct Connectivity. Here Bp means branch-point, Ep means end-point, and the value of the unit is 1 if two points are directly connected, otherwise the value is 0.

	Bp_1	Bp_2	$\cdots$	Bp_n
Bp_1	$1/0$	$1/0$	$\cdots$	$1/0$
Bp_2	$1/0$	$1/0$	$\cdots$	$1/0$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
Bp_n	$1/0$	$1/0$	$\cdots$	$1/0$
Ep_1	$1/0$	$1/0$	$\cdots$	$1/0$
Ep_2	$1/0$	$1/0$	$\cdots$	$1/0$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
Ep_n	$1/0$	$1/0$	$\cdots$	$1/0$

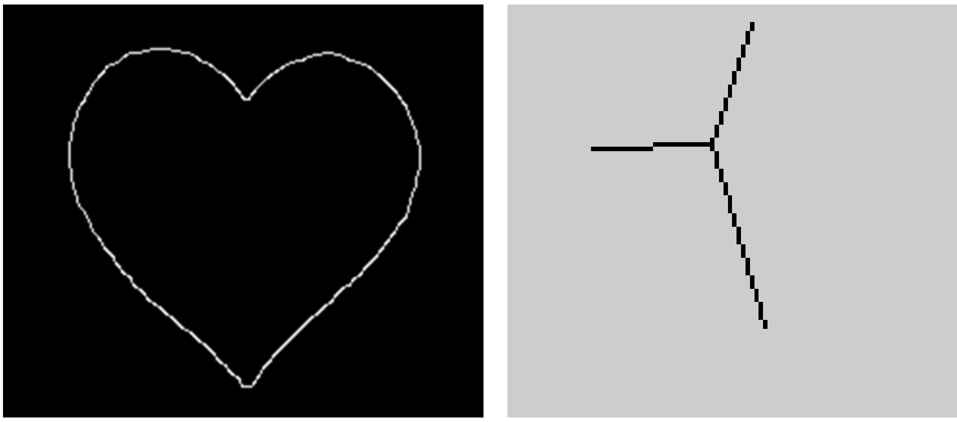
5.2.4 Origami Generation

The final step for origami pattern generation is based on the core algorithm in TreeMaker developed by Robert J. Lang. In TreeMaker, the skeleton of the object is considered as the projection of the origami base on a flat 2D surface. The goal of this algorithm is to map all the end-points and branch-points to the vertex in a 2D paper area with the constraints of edge length in the skeleton. Therefore, the paper can be divided into several polygons in the shape of a triangle or quadrilateral where basic folding, such as rabbit-ear folding, can be assigned. In the software implementation, the problem of point mapping and fold assigning is converted to the solving process of a nonlinear constrained optimization using Augmented Lagrangian Multiplier algorithm [92]. The final output of Snap-n-Fold is a square image of folding pattern that shows the lines of valley folding and mountain folding. Figure 5.6b shows a simple example of origami pattern generated from a shape of the heart in Figure 5.6a. The Figure 5.7a and Figure 5.7b show the middle steps of edge extraction and skeleton generation of the heart shape, in which the results support the generation of final crease pattern.



(a) (b)

Figure 5.6: Example of origami pattern generated from a heart shape: (a) Original image of a heart shape, (b) Origami pattern based on Figure 5.6a



(a) (b)

Figure 5.7: (a) The edge information extracted from the original image; (b) Skeleton information of the heart shape.

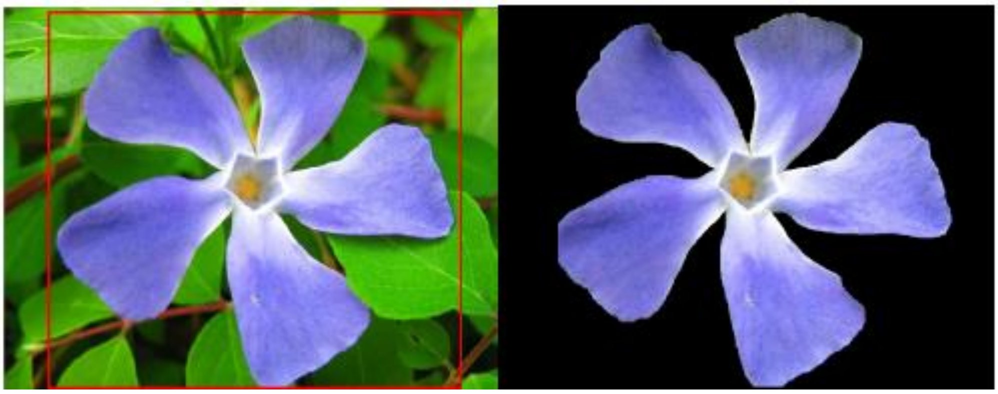
In the end, users can print out the image of origami pattern and create the origami with the similar shape of the selected object. It should be clear that the final output of Snap-n-Fold at the current stage is the folding pattern of an origami base with the correct number of vertices and edges as shown in Figure 5.8a. With the origami base, users can easily expand to create more complex origami shapes, as shown in Figure 5.8b. The techniques to do the origami shaping are widely known and available in the origami literature.

Figure 5.8: Print out and Fold: (a) User's print-out and folding, (b) Final origami love-heart

In the following, Section 5.2.5 describes an example of using Snap-n-Fold, to elaborate the results of each step of the system in details.

5.2.5 Example of Snap-N-Fold System

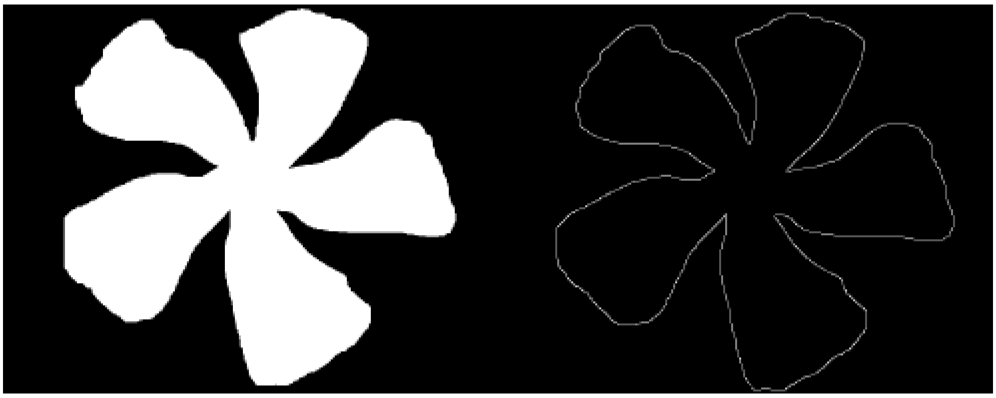
As an example, when a user selects a flower through the computer camera or image as shown in Figure 5.9a in the step of object extraction, Snap-n-Fold system will exclude the background and generate an image with only the selected object and black background as shown in Figure 5.9b.



(a) (b)

Figure 5.9: Result of Object Extraction: (a) User selects the flower from the camera image, (b) The result of selected object extraction.

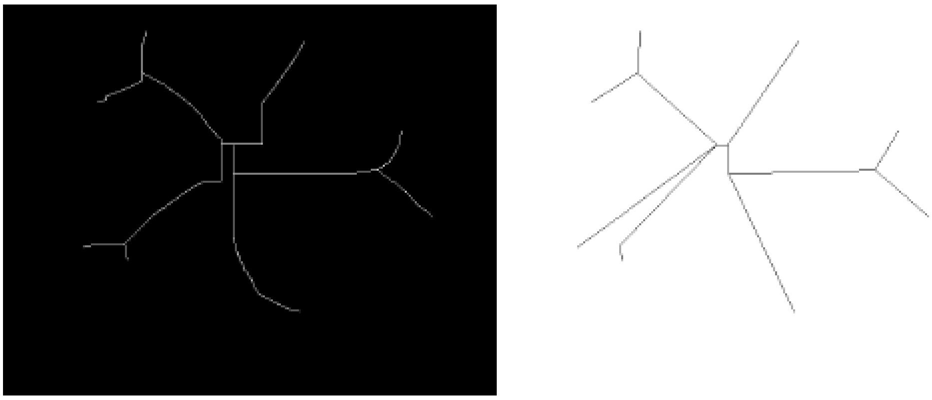
Then, for this example, as shown in Figure 5.10a, the system extracts the abstract shape of the flower using Otsu thresholding, and the resulted image is analyzed for edge detection. The result of edge detection is illustrated in Figure 5.10b.



(a) (b)

Figure 5.10: Result of thresholding and edge detection: (a) Otsu thresholding, (b) Canny edge detection

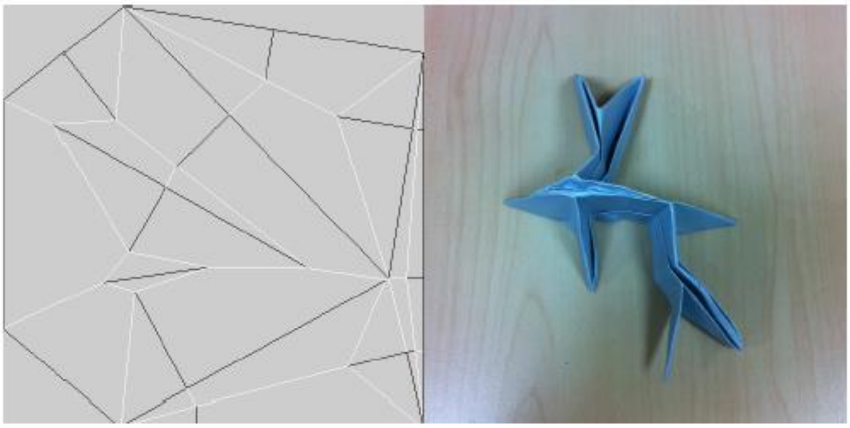
Taking the results of binary thresholding and edge detection, the system further extracts the basic skeleton of the selected object. The result of skeletonization in this example is shown in Figure 5.11a. Then end-points and branch-points are extracted from Figure 5.11a, followed by generating the connectivity table of the skeleton graph. The visualization of the connectivity table is shown in Figure 5.11b.



(a) (b)

Figure 5.11: Result of object skeletonization: (a) The basic skeleton of the selected flower, (b) Visualization of the connectivity of the skeleton graph

Finally, the connectivity of the skeleton represents the abstracted structure of the object, which is required as input for Robert J. Lang's algorithm [46] on generating origami base pattern. Therefore, the Snap-n-Fold system analyses the connectivity table using Lang's method [46] and generates the folding pattern for the origami base based on which a user can create the origami model of the selected flower as shown in Figure 5.12. Figure 5.13 shows the simulation of folding based on the generated crease pattern. The virtual paper is transformed into a polygon group in a virtual world. Each polygon is connected to adjacent polygons based on the crease information. By clicking on one polygon in the virtual paper surface, users can trigger the folding animation to simulate the actual origami folding, starting from the selected polygon and folding crease.



(a) (b)

Figure 5.12: Final result of Snap-n-Fold: (a) The generated folding pattern, (b) The physical origami based created by the pattern in Figure 5.12a

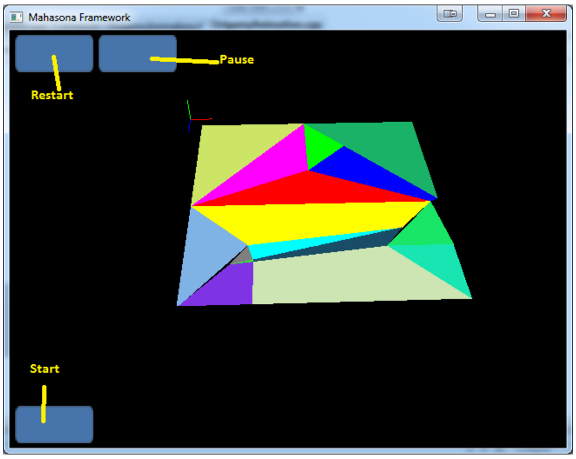


Figure 5.13: VR simulation of generated origami.

More results can be found in Figure 5.14 and Figure 5.15. Details of the middle results are shown in Appendix D.

(a) (b)

Figure 5.14: Example of Snap-n-Fold: Horse (a) User selects horse in the image, (b) Origami base generated based on the selected horse

(a) (b)

Figure 5.15: Example of Snap-n-Fold: Bird (a) User selects bird in the image (b) Origami base generated based on the selected bird

For this example, we tested the system using a desktop PC with specifications as follow: Intel(R) Core(TM) 2 Duo CPU 3GHz and 4GB RAM. In order to evaluate the result of the first prototype, we recorded and averaged the computational time of each step, as described in Table 5.2: Computational Time of Snap-n-Fold. In addition, the current version of Snap-n-Fold produces better results when there is sufficient color difference between the selected object and the background. Therefore a better algorithm for object extraction is required.

Table 5.2: Computational Time of Snap-n-Fold

Step	Computational Time (s)
Object Extraction	1.96
Object Skeletonization	0.19
Origami Generation	0.11

Furthermore, I developed a GUI-based Snap-n-Fold, as shown in Figure 5.16, to facilitate the usage of this algorithm. The user interface clearly indicates the three main steps of generating origami pattern by selecting the real-life objects from input images. In addition, the interface allows users to choose to load the image either from camera capturing stream or the computer.

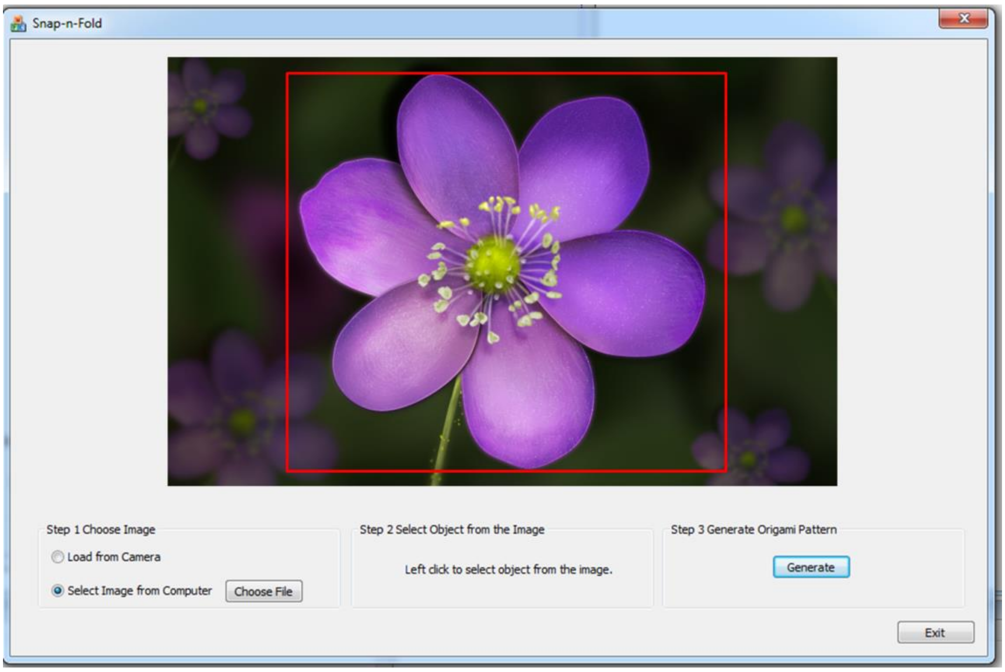


Figure 5.16: GUI for Snap-n-Fold.

5.3 User Study of Snap-n-Fold based on the Design Criteria

I studied the usage of Snap-n-Fold by inviting both experienced origami artists and origami hobbyists. We invited 20 subjects to use the prototype of Snap-n-Fold: 4 of them were origami artists with more than 5-years of experience, and the rest were origami hobbyists who have played origami for less than 1 year. The ages of the users ranged from 17 to 45 years (M=29, SD=3.72). Only one user participated in the study at a time, and one whole user study lasted 30 minutes. Firstly, the facilitator spent around 15 minutes for tutoring on how to use Snap-n-Fold, mainly demonstrating the three main steps of generating origami pattern (Step1: load image, Step 2: select object, Step 3: generate origami pattern). After this introductory session, the user was allowed a 15-minute session to freely use the Snap-n-Fold system. After using the Snap-n-Fold software, the user completed a questionnaire for rating his/her experience. The questionnaire for using Snap-n-Fold, as shown in Appendix E, was designed based on the design criteria for TEMPC.

- Ease to Learn

All of the subjects found it was simple for them to follow the three steps to generate origami patterns by selecting real-life objects from the loaded images. The related statements all scored on average more than 4/5.

- Ease to Use

Most of the experienced origami artists could successfully fold the origami base using Snap-n-Fold by following the generated origami pattern and the VR animation. On the other side, origami hobbyists with less experience found it difficult to follow the animation to create the real folding by themselves, although they could easily generate the origami pattern using Snap-n-Fold. One origami artist mentioned that Snap-n-Fold could certainly help him to design a new origami pattern, but it is still hard for beginners to follow the pattern since the origami pattern is originally made for experienced players. Therefore, we can form a conclusion that Snap-n-Fold is more useful for experienced origami artists.

- Usefulness & Low cost

All the users mentioned that the algorithm worked well and fast, and that there was no system crash during all the user studies. Furthermore, its usefulness was demonstrated by the origami base created by experienced origami artists during the user study, as shown in Figure 5.17, Figure 5.18, Figure 5.19, and Figure 5.20. Details of the middle results of each work are shown in Appendix D.

Figure 5.17: Origami generated from the photo of a swan.

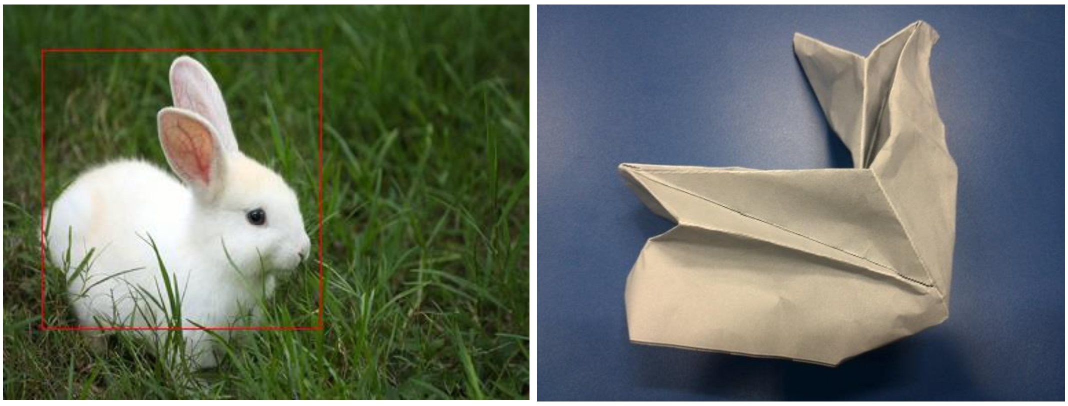


Figure 5.18: Origami generated from the photo of a rabbit.

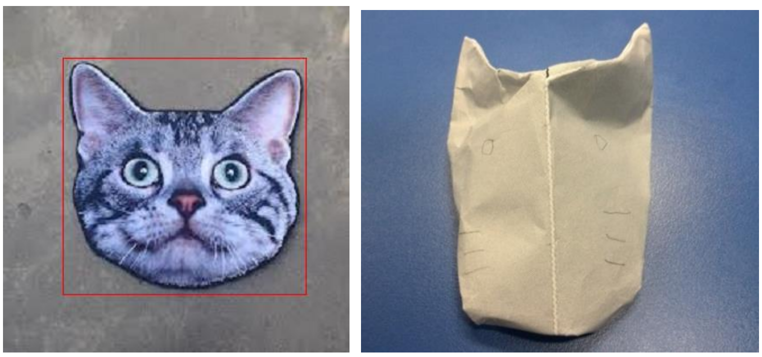


Figure 5.19: Origami generated from the photo of a cat.

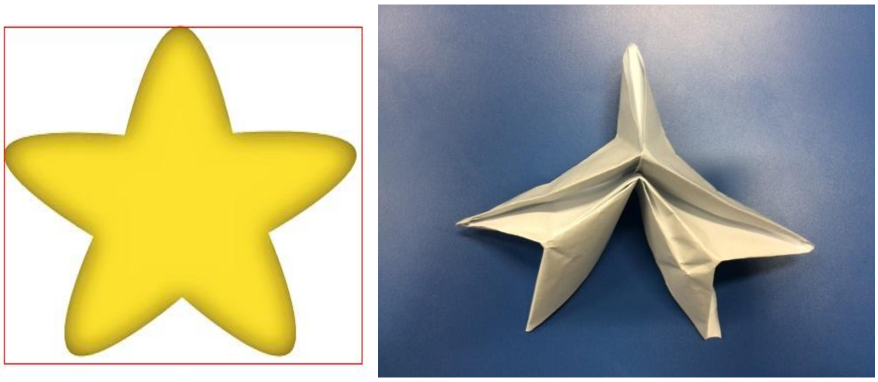


Figure 5.20: Origami generated from the clip art of a star.

While the software interface allows users to choose to load the image either directly from the computer or the real-time camera capturing, most of the subjects preferred loading images from the computer. One subject stated that the images from the camera would also be affected by shaking hands. Finally, all the users stated they were willing to pay for this software. Details of the results of this user study are shown in Appendix F.

5.4 Summary

Snap-n-Fold is a computer-vision-based system that generates origami pattern based on the structure of real-life objects. It aims to facilitate and enhance the folding movement of paper craft. However, the user study showed that it is difficult for inexperienced origami hobbyists to use the system to successfully create the physical foldings; they preferred more easy-made paper craft in the TEMPC systems.

In summary, from the develop of Origami Tower (Chapter 4) and Snap-n-Fold (Chapter 5), we learned that the taxonomy with QOC design space provides a method of inspiring and reasoning new TEMPC systems. Secondly, an easy-made paper craft, not complex origami, is more preferable. Users enjoyed using everyday accessible paper materials for TEMPC systems instead of being required with specific set-up in paper craft. Users preferred TEMPC systems which allow them to create and control their own paper craft. User’s preference on ease of making, controllability, and tangibility, motivated me to look into hardware–based output of TEMPC. The analysis of the TEMPC taxonomy suggested that SMA (shape-memory alloy) is popularly used in generating tangible output movement in TEMPC, but it is hard and expensive to use in order to provide better control. Operating laser-generating devices and controlling circuits embedded in paper craft require engineering skills in hardware design and development. Therefore, I developed a new technology called selective inductive power transmission, which simplifies the hardware embedded in paper craft. Details of this technology will be presented in Chapter 6.

Chapter 6 Selective Inductive Power Transmission for Paper Computing[4]

The exportation presented in Chapter 4 and Chapter 5 formed my second contribution on user preference on TEMPC systems, suggesting that users prefer more accessibility, controllability, and tangibility in TEMPC systems. In this chapter, I present my third contribution, the technology of Selective Inductive Power Transmission (SIPT) which automates physical paper movements with embedded hardware in paper material through alternative electromagnetic field. The power transmitter can be controlled to activate different receivers selectively in the context of wireless power transferring with multiple receivers. The technology was achieved by changing the output frequency of the power transmitter and the impedance of the receivers.

6.1 Fundamental Theory of Selective Inductive Power System

The fundamental principle of this method is based on the theory of electromagnetic power generation. During the 19th century, the basic theory on electromagnetic field proved that an electric current produces a magnetic field, and a changing magnetic field produces an electric field. In the late 1890s, Nikola Tesla [58] demonstrated a series of experiments of magnetic resonant power transmission. The abstract model of inductive wireless powering is as shown in Figure 6.1, where primary coil A is connected to a high-frequency AC power, and secondary coil is connected to the load.

[4] Publication:

1. Kening Zhu; Hideaki Nii; Owen Noel Newton Fernando; Jeffrey Tzu Kwan Valino Koh; Karin Aue; Adrian David Cheok. Designing Interactive Paper-Craft Systems with Selective Inductive Power Transmission. Interacting with Computers 2013; doi: 10.1093/iwc/iws019. Impact Factor: 1.233
2. Kening Zhu, Hideaki Nii, Owen Noel Newton Fernando, and Adrian David Cheok. 2011. Selective Inductive Powering System for Paper Computing. In Proceedings of the International Conference on Advances in Computer Entertainment Technology (ACE '11).

Therefore, energy is transferred from coil A to coil B wirelessly, relying on high frequency-changing magnetic flux.

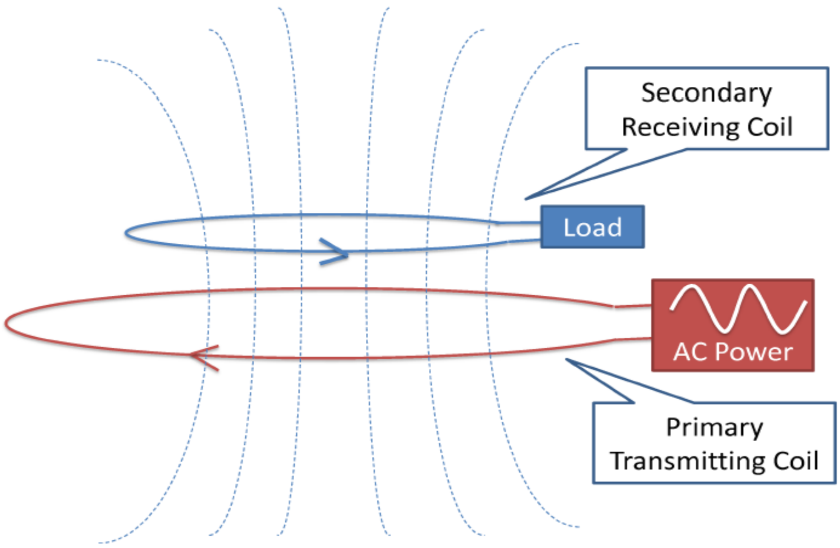


Figure 6.1: Model of Inductive Wireless Powering between Two Coils

When there are multiple receiving coils with different resonant frequencies and impedances, the output frequency in the primary transmitting coil can be changed to activate different receiving coils resonantly. According to the equation below, the impedance of a receiver is determined by its inductance and capacitance.

$$f_{resonant} = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

In order to achieve different impedances and resonant frequencies, as shown in Figure 6.2, each receiving coil is connected to a small capacitor with a particular value which determines its resonant frequency. The receiver circuit can be considered as a band pass filter with center frequency, $f_{resonant}$, which is the resonant frequency according to its impedance.

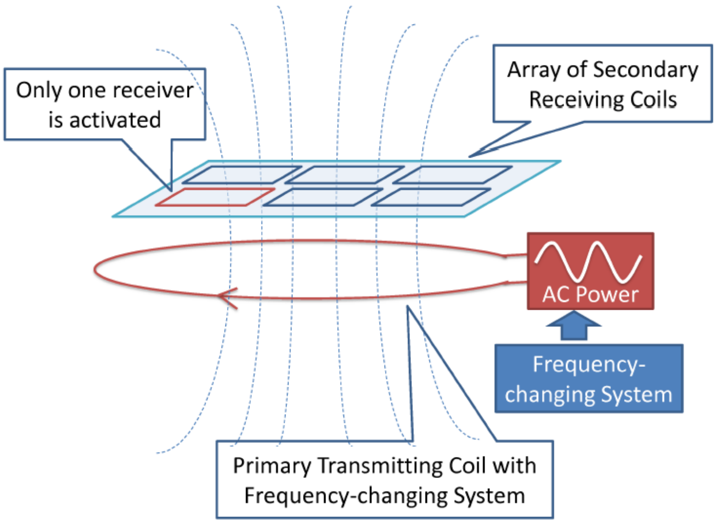
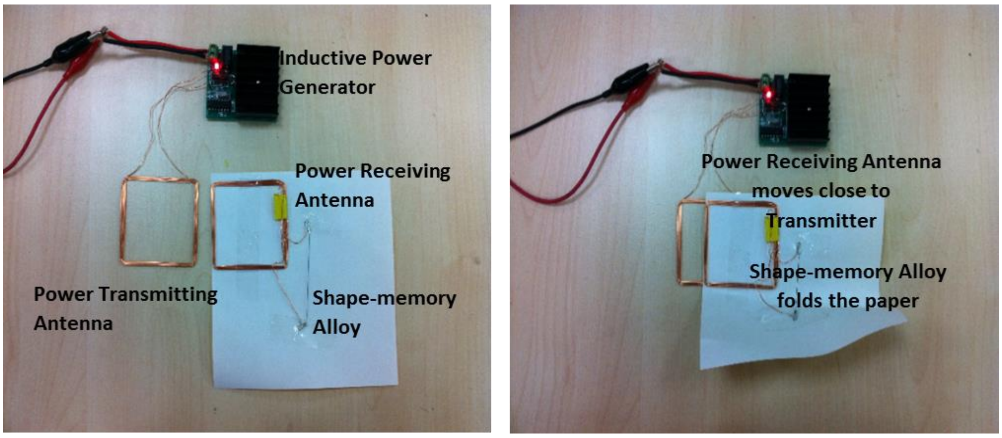


Figure 6.2: Inductive Wireless Powering with Multiple Receiving Coils

As a first step, I explored the method of inductive power by integrating it with paper craft. As shown in Figure 6.3a, I implemented a basic inductive powering system using a crystal oscillating circuit where the power-transmitting coil and the power-receiving coil have the same geometry, dimension, and number of turns. I connected the power-receiving coil to a shape-memory-alloy (SMA) wire and embedded them into paper material. As shown in Figure 6.3b, SMA received electrical power through the inductive magnetic field and folded the paper.



(a) (b)

Figure 6.3: First trial of the integration of inductive power and paper craft

The initial results showed that inductive power transmission can be used for paper computing. However, most paper-craft arts are made using complex combinations of various single manipulations, such as folding, cutting, bending, etc. As stated in the framework of Organic User Interface (OUI) [34], the OUI computing devices will be able to "actively alter their shape; the 3D physical shape itself will be a form of display, and its kinetic motion will become an important variable." Although the application in the technology of selective inductive power transmission shares similarities with these projects in exploring how to sense and actuate interactive shape-changing paper, its advantage is that this method of integrating selective inductive power transmission with paper tends to eliminate physical power connection to the TEMPC. This advantage maintains the customizability and the tangibility for users to directly interact with these paper crafts by hand.

6.2 Related Work in Inductive Power Transmission for Multiple Receivers

The presented technology of selective inductive power transmission is highly related to the research of resonant inductive power transferring in the context of multiple power receivers. Travis Deyle and Matt Reynolds [20] introduced a simple and low-cost inductive power surface which can provide electrical power wirelessly to multiple mobile swarm robots. Their system consists of a 60cm x 60cm power surface with a large and high-Q L-C resonator located beneath the surface. The demonstration showed that the system powered up five autonomous swarm robots to move and communicate on the surface at the time. Benjamin L. Cannon et al. [10] presented their research on using magnetic resonant coupling to transfer wireless power to multiple small receivers. In their presentation, parallel capacitors are added to power-receiving coils to form a resonant circuit for specific operating frequencies. Their experimental results showed that with different capacitors, wireless power can be provided to different receivers separately. More recently, Akihito Noda et al. [66] developed 2DWPT system, which consists of a flat 2D sheet to wirelessly power up multiple power-receiving couplers on top of it and prevent general objects from receiving power from high-Q resonant. The experiment reported high power transmission efficiency of the system.

Compared to these related research, selective inductive power transmission took one step forward to develop the full system with both frequency-changeable power transmitter and a set of resonant power receivers. In this system, inductive electrical power can be transferred to more than ten power receivers separately as the impedance of each power receiver is tuned to one specific resonant frequency generated by the power transmitter. The results of both software simulation and hardware experimentation showed the potential of increasing the number of power receivers. In addition, the small and thin power receivers create the possibility of embedding this technology into TEMPC and enable paper to receive power without wire connection.

6.3 Categorization of Existing Technology-enhanced Movable Paper Craft based on Power Requirement

In order to understand the power requirements of different types of TEMPC, I first summarized the actuating elements that trigger paper craft output used in the existing projects discussed in Chapter 2. Most of these components are small in size, flexible, and easily integrated into paper material. Three types of actuating components were mainly used in paper-craft interaction: LED, Nichrome wire, and SMA material. Table 6.1 shows the details of the functions for different related paper-craft projects and the power consumption of these components. The paper-actuating components require low power to be activated, which also motivated me to develop the technology of SIPT and integrate it with paper crafts to support as many types of actuated manipulation as possible.

Table 6.1: Descriptions of popular actuating components for TEMPC

Type	Function	Power-related features	Existing projects
SMA	Movement (folding, bending, scrunching, rolling, etc.)	An SMA spring of 5 cm from Toki (Biometal) has a resistor of 30 Ohm and requires 0.1A to trigger a shape change.	Interactive Paper Devices [76], Animating paper using shape-memory alloys [70], Electrical Popables [71], Animated paper [43], Move-it [69]
LED	Emissive display (coloring)	Above 2V to light up	Electrical Popables [71]
Nichrome wire	Temperature change, cutting	A nichrome wire of 5 cm has a resistor of 2 Ohm. With a current of 0.5A, the temperature is 40◦, while with a current of 1.5A, the temperature reaches 160◦ to cut paper	

6.4 Software Simulation

First I simulated the hypothesized method in SPICE [48] software environment. As shown in Figure 6.4, there are two resonant circuits in the schematic: power transmitter and power receiver, linked by coupling coefficient K1. On the left side of the schematic, the transmitting coil is excited by a sinusoid power source with the amplitude of 50V. A single-turn coil is modeled as an inductor (L1) with resistance (R1). On the right side, which represents the part of power receiving, the receiving coil consists of inductor (L2) and resistance (R2). The receiving coil is also physically connected to an external capacitor (C1) for frequency matching, and the load resistor (R3). Finally, transmitter L1 and receiver L2 are connected with coupling coefficient K1.

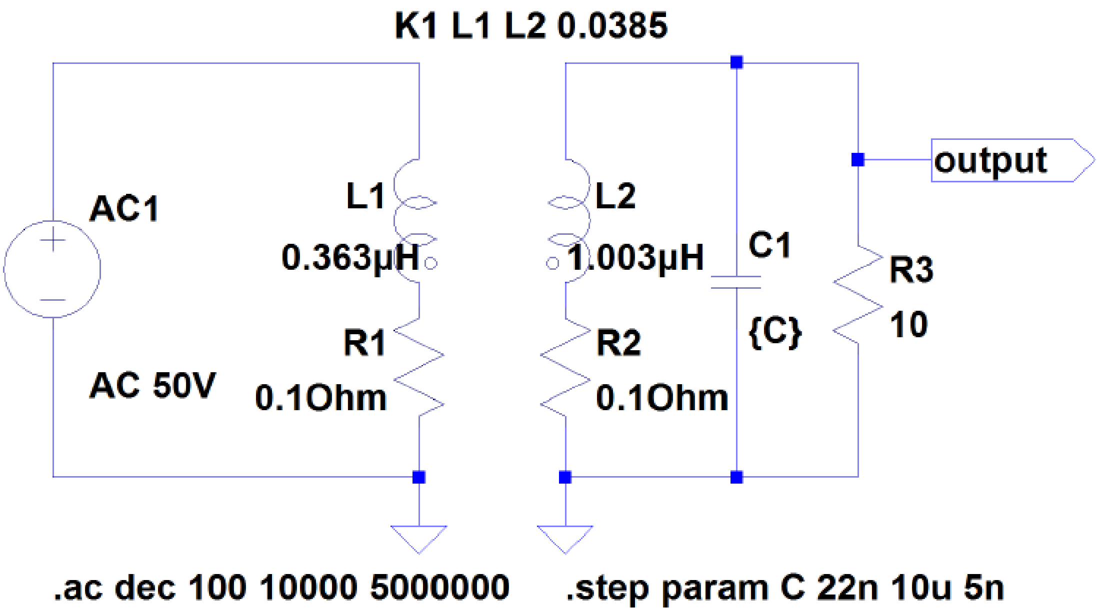


Figure 6.4: Simulation of the Wireless Powering System

The transmitter is modeled as a 1-turn transmitting coil with the diameter of 20cm, and the calculated inductance for L1 using Equation 2 has the result of 0.363uH. For the receiver, I used the model of a 4-turns receiving coil with the diameter of 2.5cm. Based on Equation 2, the result for the inductance of L2 is 1.003uH. The coupling coefficient K1 between the transmitter and the receiver is calculated using Equation 3 with the result of 0.0385.

$$L = N^2 R \mu_0 \mu_r [\ln(\frac{8R}{a}) - 2] \quad (2)$$

where,

N: Number of turns

R: Radius of the circle

a: Wire radius

r: Relative permeability of the air

$$M = \frac{\mu \pi N_1 N_2 r_1^2 r_2^2}{2\sqrt{(r_1^2 + x^2)^3}} \quad (3)$$

where,

r_1 : Radius of transmitting coil

r_2 : Radius of receiving coil

N_1: Number of turns of transmitting coil

N_2: Number of turns of receiving coil

x: Distance between two coils

In this simulation, the output frequency of the transmitting coil is sweeping from 10 kHz to 5 MHz, and the value of the attached capacitor (C1) in the receiver ranged from 22nF to 10uF. Figure 6.5 shows the waveforms of both transmitter and receiver in the condition of output frequency f = 336 kHz and the receiver capacitance C = 0.22uF.

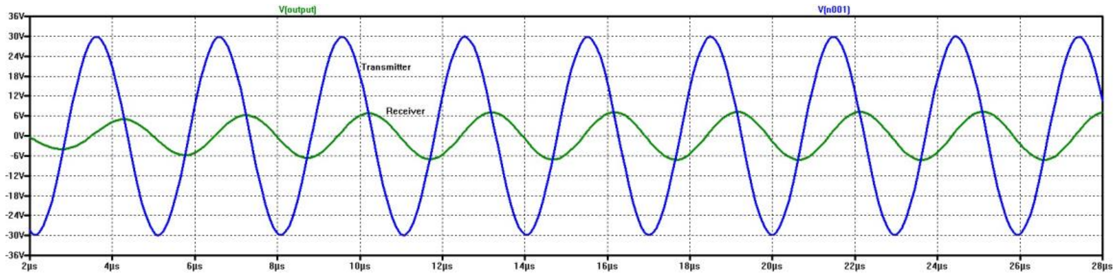


Figure 6.5: Example waveforms of simulation: f = 336 kHz, C =0.22uF

The final result of the simulation is shown in Figure 6.6. It is easily observed that peak inductive power can be separated for different receivers in different frequencies; from 68nF to 10uF especially, for one particular capacitance the peak power is higher than the other values of power for other capacitance. This means multiple receivers can be distinguished using different output frequencies and different capacitors.

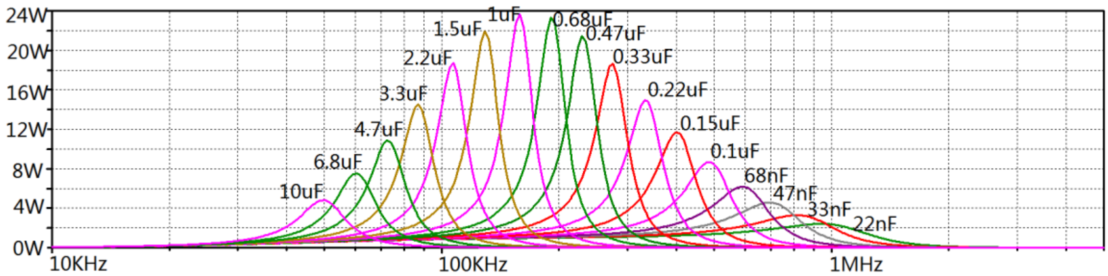


Figure 6.6: Simulation Results

Table 6.2 shows the peak powers corresponding to simulated resonant frequencies. The simulation provides the guidance for us to implement the hardware prototype of selective wireless powering.

Table 6.2: Simulated Result: Peak Power - Resonant Frequency

Capacitance	Resonant Frequency	Peak Power
68nF	591.0 kHz	6.2W
0.1uF	488.2 kHz	8.7W
0.15uF	400.8 kHz	11.7W
0.22uF	322.9 kHz	15.0W
0.33uF	276.5 kHz	18.6W
0.47uF	227.9 kHz	21.5W
0.68uF	191.5 kHz	23.3W
1uF	159.1 kHz	23.6W
1.5uF	128.7 kHz	22.0W
2.2uF	107.3 kHz	18.7W
3.3uF	87.1 kHz	14.6W
4.7uF	72.5 kHz	10.9W
6.8uF	60.2 kHz	7.6W
10uF	50.1 kHz	4.8W

6.5 Hardware Development

Two prototypes of selective inductive power were developed based on two different technologies: L-C resonant oscillator and power amplification of sinusoid function generator. We then compared these two prototypes by experiments, and according to the experimental results, selected the better one for different contexts of application in paper computing. The following part of this section will describe and compare these two systems in detail.

6.5.1 First Prototype: LC Resonant Oscillator

1) Power Transmitter:

Figure 6.7 illustrates the basic schematic of LC-based power transmitter. The basic idea is to feed a parallel L-C tank circuit from an AC voltage source at its resonant frequency, which allows large reactive current to circulate in the circuit while only real power is being drawn from the source. This sets up a large alternating magnetic field in the inductor, which is designed as a single conductive loop in this case. Therefore, different frequencies can be generated by changing the capacitance of the LC transmitting circuit.

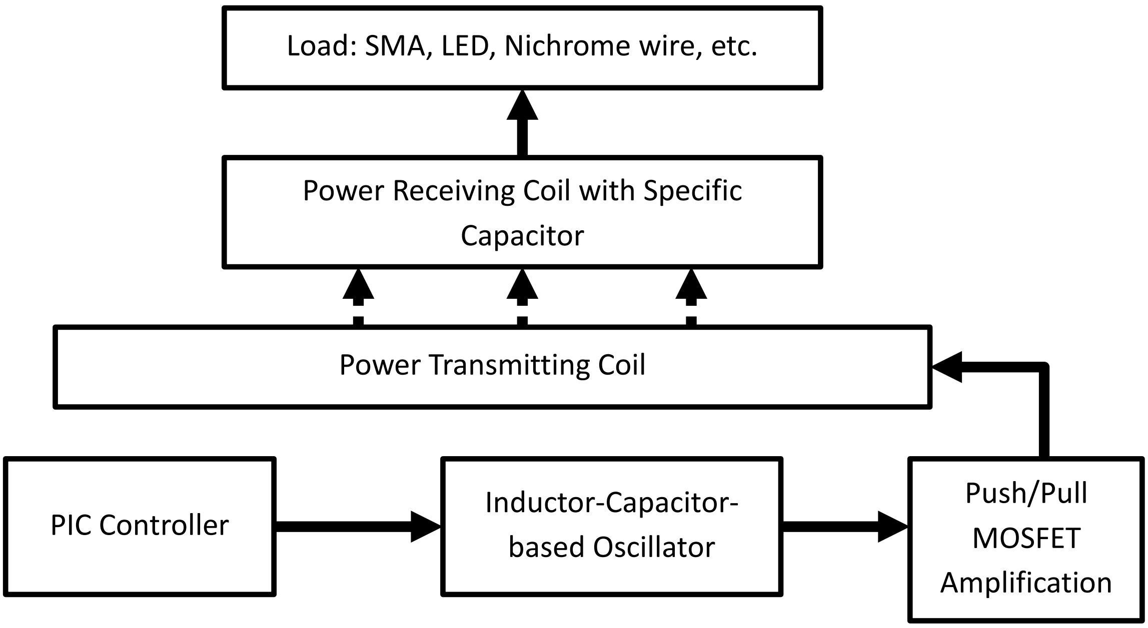


Figure 6.7: Overall diagram of the inductor–capacitor-based SIPT

As shown in Figure 6.8, the transmitter was built with a high output power push/pull MOSFET oscillator setup. The LC tank in the system generates the oscillation and two power MOSFETs amplifies it to enable the system to transfer more energy wirelessly. Ten polypropylene capacitors are respectively controlled by a relay and a switch so different capacitance values can be included at runtime to generate a variety of frequencies. The values of the ten capacitors are selected, described in Table 6.3, based on the results of resonant frequencies in software simulation and Equation 1.

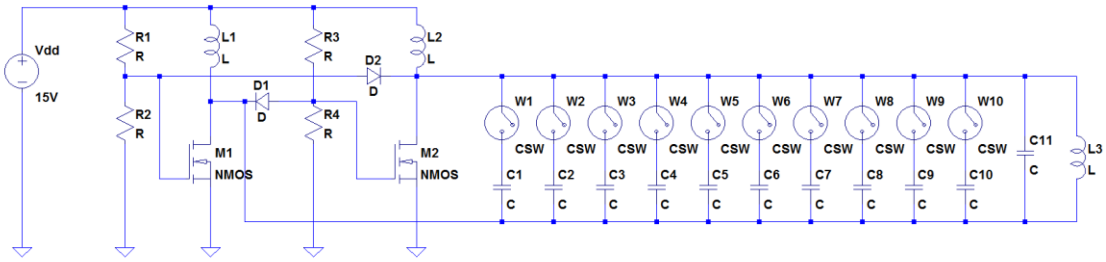


Figure 6.8: Overall schematic of LC-based power transmitter

Table 6.3: Types of capacitors used in the LC-oscillating circuit.

Capacitance	Amount
0.22uF	2
0.33uF	2
0.68uF	1
1uF	1
2.2uF	1
3.3uF	1
4.7uF	1
6.8uF	1

The transmitter prototype also includes digital controlling interface for decrypting the input from an external command to control the frequencies that are being emitted by the transmitter. We chose a PIC micro-controller with built-in serial communication capability and enough output pins to control the relays. However, the current of the PIC may not be sufficient for the relays. Thus, a driving circuit was implemented as shown in Figure 6.9. The current from the PIC will be amplified by the NPN Bipolar Junction Transistor. A diode is reversely connected between the relay coil to protect the PIC and BJT from the back EMF pulse generated when turning off the relay.

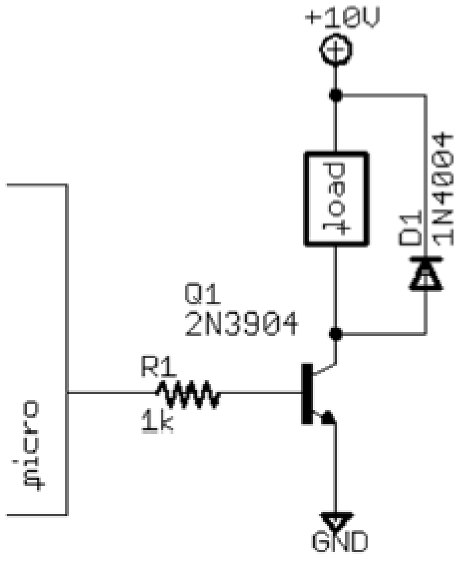


Figure 6.9: Schematic of Relay Driver

In the PCB prototype, as shown in Figure 6.10, a one-turn antenna with a diameter of 200mm is made of 6mm copper loop and its inductance is approximately 0.363uH. Copper loop is chosen for its small resistance, as over 20A current will be circulating within the antenna during operation. The system can transmit 60V peak to peak electromagnetic waves at 12V input DC voltage. In addition, a high-voltage-rating polypropylene-film capacitor must be used to avoid the large current burning the capacitors during operation.

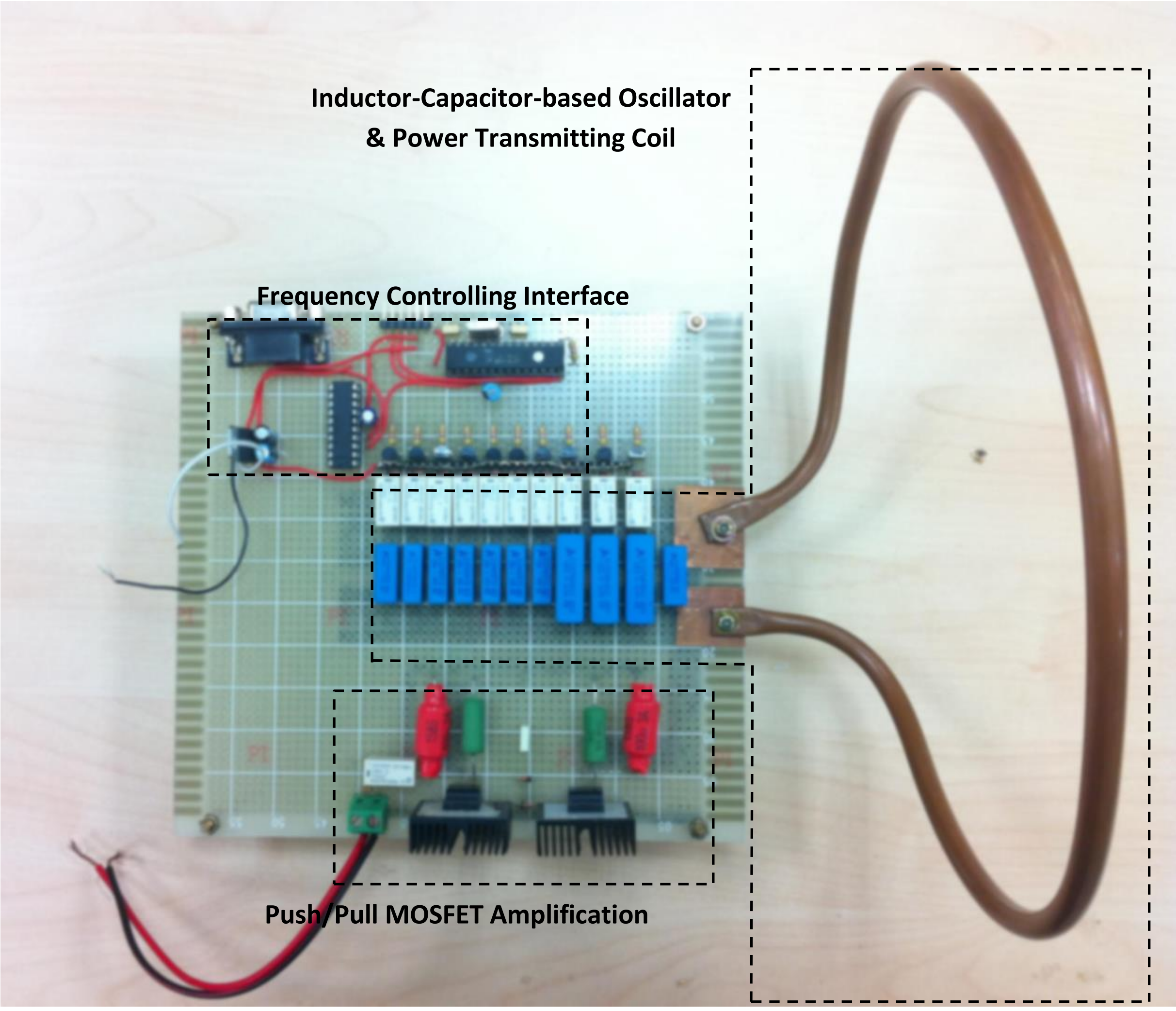


Figure 6.10: Prototype of power transmitter

2) Power Receiver:

In the prototyping of the receiving coils embedded in the paper, we used an 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 a diameter 2.5cm and has only 4 turns to match the small resistance of the heating wire. The capacitor and the load resistor are connected to 2 nodes of the copper coil. Each coil will have a different value capacitor attached. Thus each will have different resonance frequency. The physical prototype of the receiving part is shown in Figure 6.11.

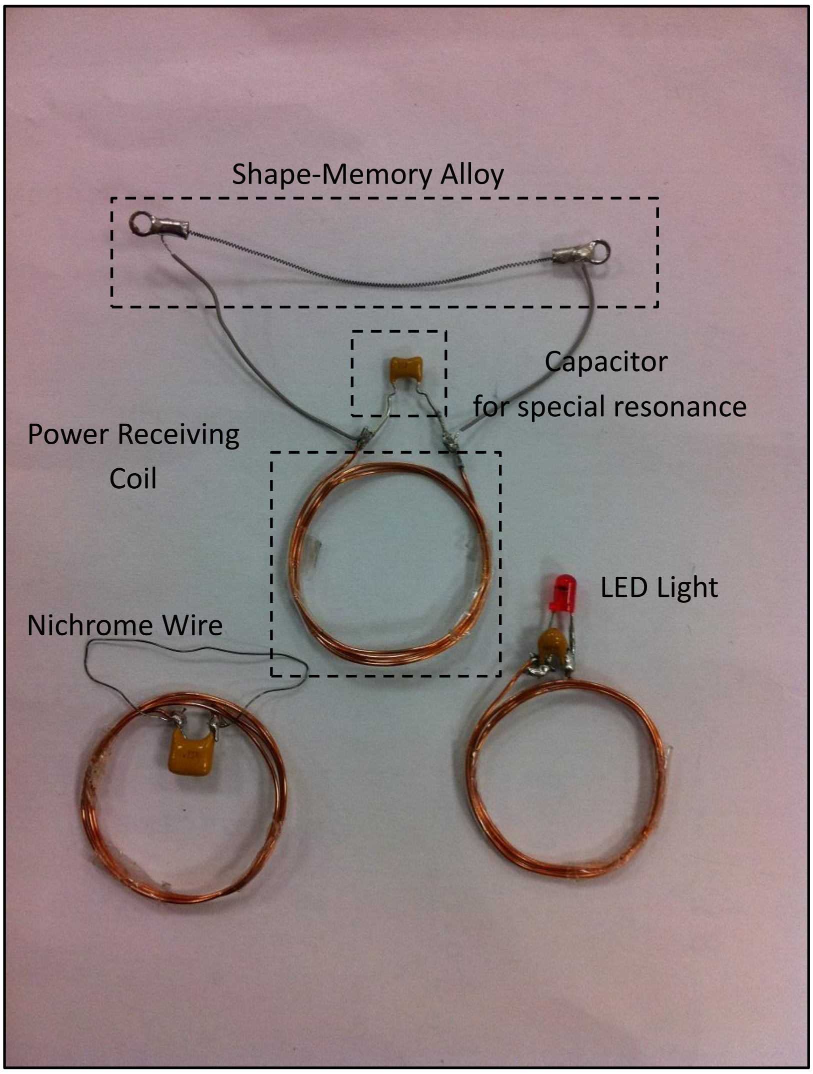


Figure 6.11: Prototype of power receiver

3) Performance Experiment:

Actual experiments with the prototype were conducted with 13 different values of capacitance in the receiving side. Different frequencies were generated without the distortion of the output waveform. Figure 6.12 shows an example of the waveform in the frequency of 511 kHz plotted from oscilloscope.

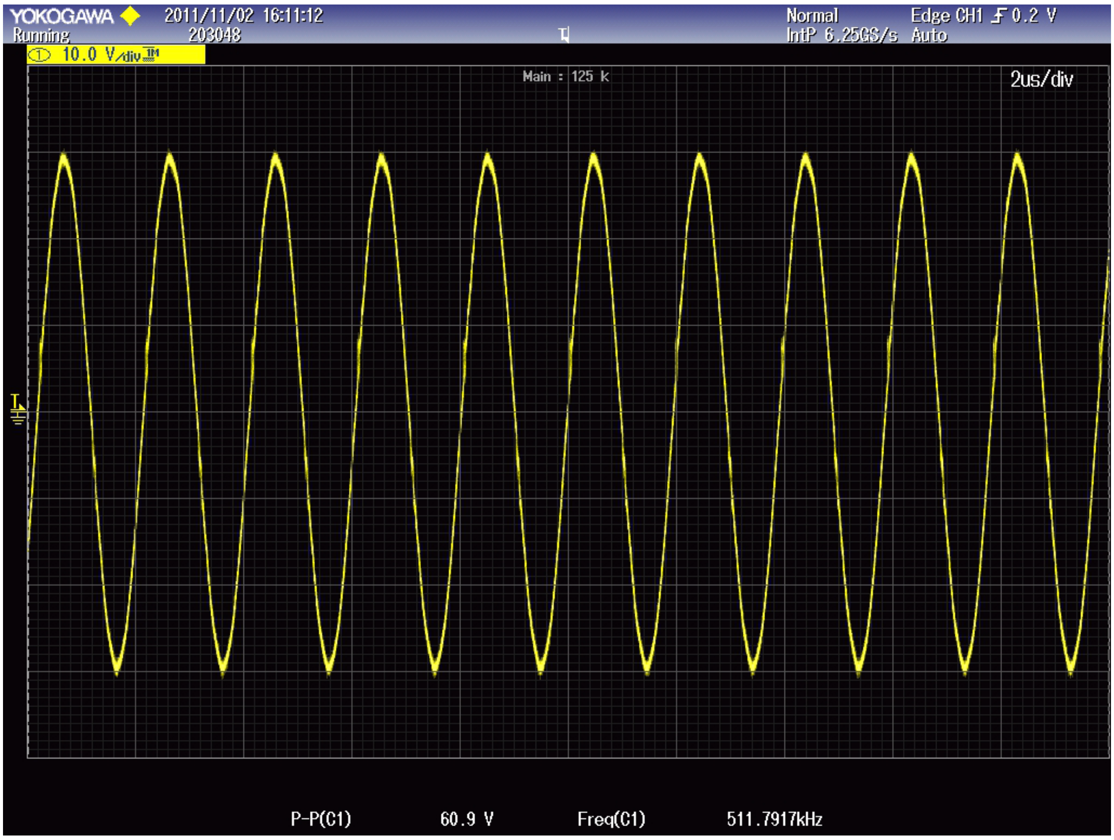


Figure 6.12: Example output waveform of power transmitter: f = 511kHz

The mapping between the capacitance of the LC transmitter and the output frequency is shown in Table 6.4, where 1 means the capacitor is connected and 0 means the capacitor is not connected. Therefore, with different combination of capacitors, the power transmitter can output 13 different frequencies which are close to the results of software simulation.

Table 6.4: Experimental results of output frequency

0.22uF	0.22uF	0.33uF	0.33uF	0.68uF	1uF	2.2uF	3.3uF	4.7uF	6.8uF	Total Capacitance	Generated Frequency
1	0	0	0	0	0	0	0	0	0	0.22uF	563.5 kHz
0	0	1	0	0	0	0	0	0	0	0.33uF	460.1 kHz
1	1	0	0	0	0	0	0	0	0	0.44uF	398.4 kHz
0	0	1	1	0	0	0	0	0	0	0.66uF	325.3 kHz
1	0	0	0	1	0	0	0	0	0	0.90uF	278.6 kHz
0	0	1	0	0	1	0	0	0	0	1.33uF	229.2 kHz
0	0	1	0	1	1	0	0	0	0	2.01uF	186.4 kHz
1	0	1	0	0	0	1	0	0	0	2.75uF	159.4 kHz
0	0	0	0	0	1	0	1	0	0	4.30uF	127.4 kHz
1	0	1	0	0	0	1	1	0	0	6.05uF	107.4 kHz
1	0	0	0	0	1	0	1	1	0	9.22uF	87.1 kHz
0	0	0	0	1	1	0	0	1	1	13.18uF	72.8 kHz
1	1	1	1	0	1	1	1	1	1	19.1uF	60.5 kHz

During the experiment of power transferring, a set of 13 receiving coils was placed 2cm on top of the power transmitter, and only one receiving coil was measured at a time. Figure 6.13 shows the waveforms of both transmitter and receiver at the conditional f = 352 kHz and $C_{receiver}$ = 0.22uF. The peak value of the inductive voltage was attained from the oscilloscope, and the power was calculated using the following equation:

$$P = \frac{V_{peak}^2}{2R_{load}} \quad (4)$$

The experimented results are shown in Figure 6.13. Table 6.5 shows more detailed experimental results of peak power and resonant frequency.

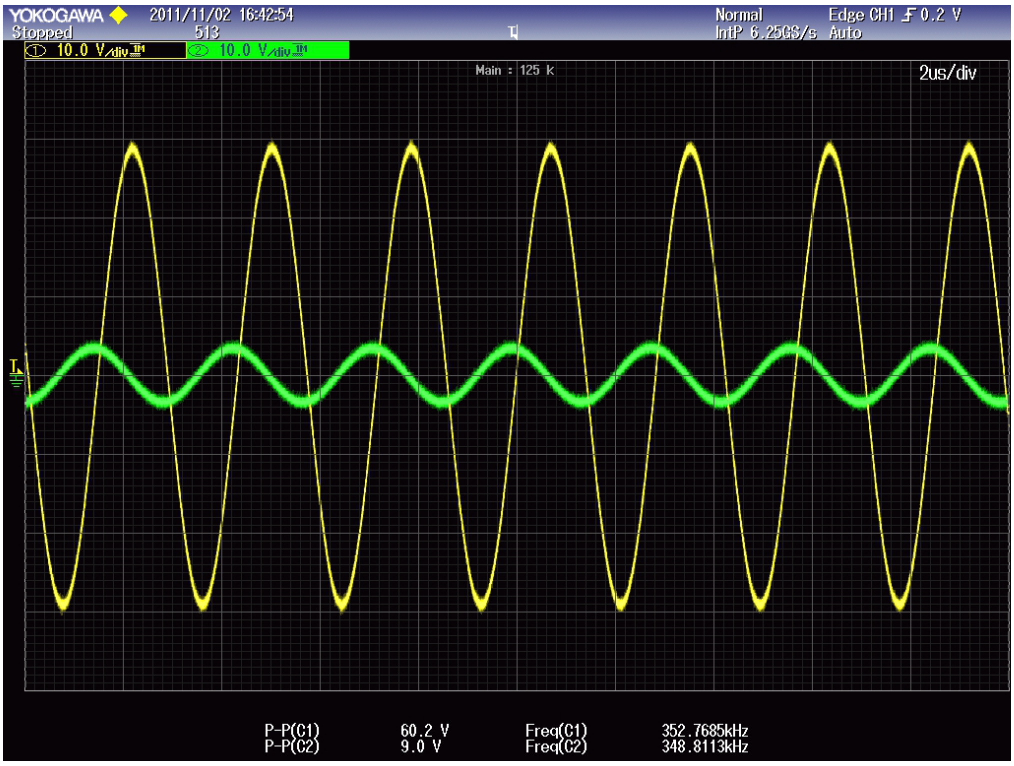


Figure 6.13: Example waveforms for transmitter and receiver: yellow-transmitter, green – receiver

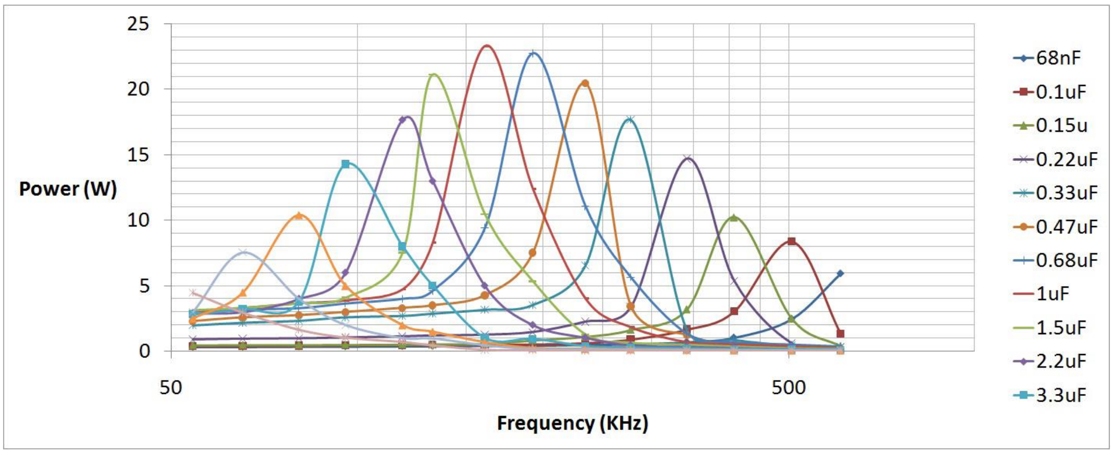


Figure 6.14: The Experiment Results

Figure 6.14(experimental results) shows a similar trend where the curves are more condensed in the range of lower frequency. Table 6.5 shows similar results of peak power as Table 6.2 (simulation) does, with the average error of 4.3%, which could be caused by the influence of peripheral devices in the physical environment. In summary, both simulated and experimental results approximately match each other and prove the method of selective inductive power transmission using oscillation generation.

Table 6.5: Experimental Result: Peak Power - Resonant Frequency

Capacitance	Resonant Frequency	Peak Power
68nF	563.5 kHz	5.9W
0.1uF	460.1 kHz	8.4W
0.15uF	398.4 kHz	10.2W
0.22uF	325.3 kHz	14.7W
0.33uF	278.6 kHz	17.6W
0.47uF	229.2 kHz	20.5W
0.68uF	186.4 kHz	22.8W
1uF	159.4 kHz	23.3W
1.5uF	127.4 kHz	21.1W
2.2uF	107.4 kHz	17.7W
3.3uF	87.1 kHz	14.2W
4.7uF	72.8 kHz	10.4W
6.8uF	60.5 kHz	7.5W

6.5.2 Second Prototype: Power Amplification of Sinusoid Function Generator

The second implementation of selective inductive power was achieved by amplifying the small output signal of the sinusoid function generator. As shown in Figure 6.15, the function generator is connected to a PC terminal through RS-232 serial port and receives control commands to adjust the frequency and amplitude of the output sinusoid signal. Then the raw signal is transferred to the RF power amplifier to achieve high power for final inductive power transmission.

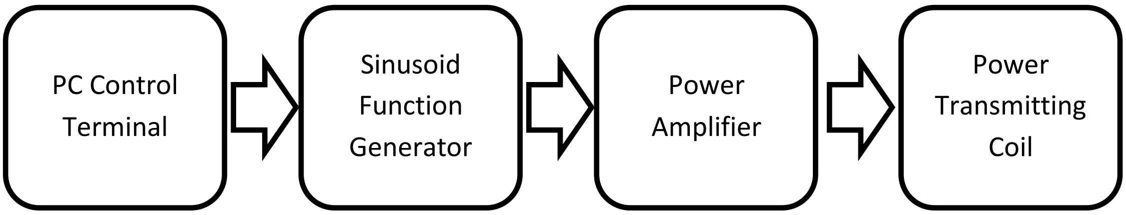


Figure 6.15: Overview of the method based on the power amplifier

SEFRAM 4422-20 MHz DDS function generator1 is used in this prototype, connected to a PC through RS-232 serial port. The function generator can be controlled by sending SCPI2 command through serial port. After receiving the command of output frequency and amplitude, the function generator first reduces the current amplitude to 0.01V, which is small enough to protect the whole system for the change of output frequency that causes the change of the impedance of the system. Then the function generator sets the output frequency to the desired value and adjusts the amplitude slowly according to the PC command.

However, the power of the function generator output is subtle and not enough for the system. I developed a Class AB power amplifier, as shown in Figure 6.16, with two transistors 2SC2565 that can provide 15A collector current and 80 MHz transition frequency. All transformers are self-made and have different functions. The first transformer is an impedance converter because the input impedance of the amplifier is 50 ohms and the input impedance of the transistor is much smaller. The second transformer separates the input signal into two small but opposite signals. The third and the fourth transformer are used to pass DC signal. The last transformer combines the two signals together to form the output signal. The function of the bottom left part is to provide DC bias voltage to the transistors. This structure (Q3 & Q4) maintains the output DC bias voltage at 0.6V. Adjusting the value of rheostat (R3) to set the bias collector current at 50mA makes two transistors work as Class AB amplifier. When AC input signal comes in, transistors produce large current.

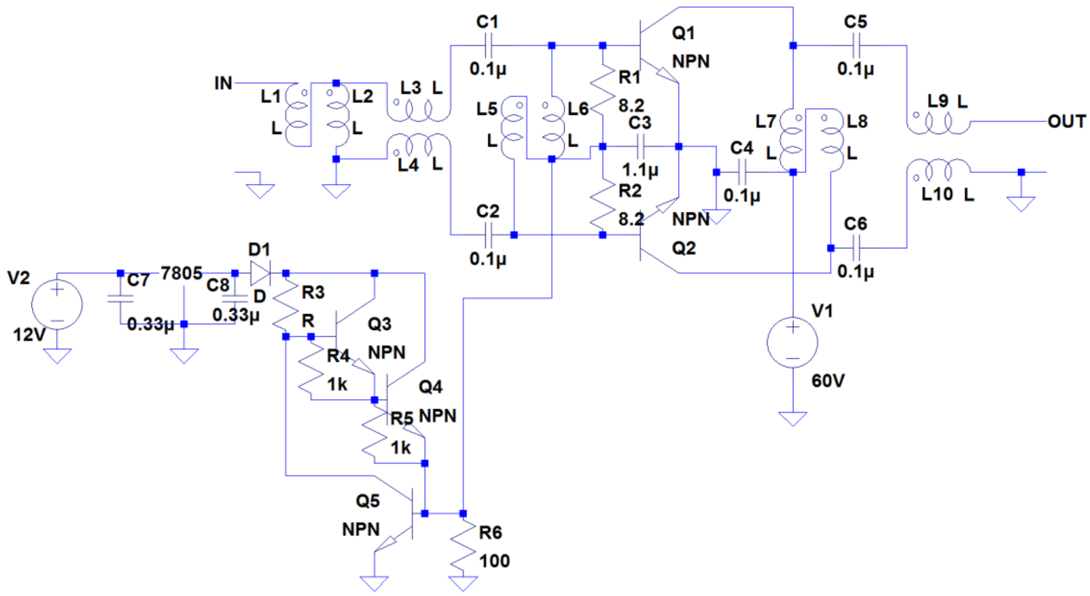


Figure 6.16: Schematic of power amplifier

The experimental prototype of the power amplifier is as shown in Figure 6.17. When the transmitting coil was connected to the amplifier, the output wave was distorted, and only very small power is output from the system, as shown in Figure 6.18.

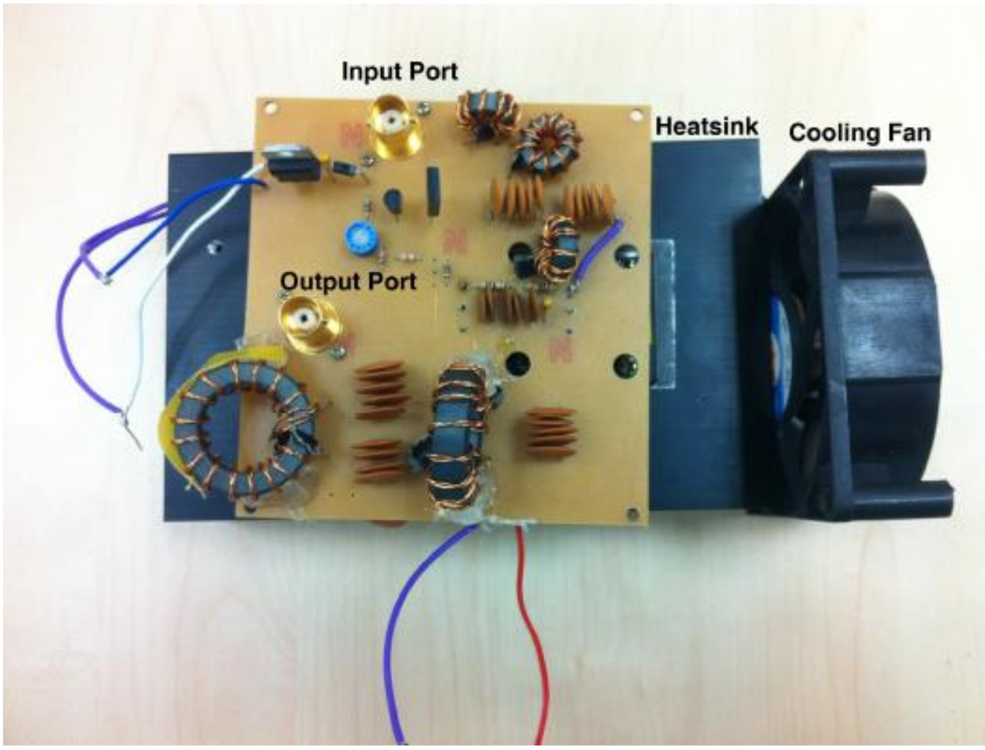


Figure 6.17: First prototype of power amplifier

Figure 6.18: Distorted output waveform from one power amplifier

Therefore, two RF power amplifiers are connected serially to form a big amplifier with better performance, which means the output of the first amplifier would be the input of the second amplifier, as shown in Figure 6.19. In order to cool down the heated transistors during the experiment, I integrated heat sinks and fans in the final prototypes to achieve the best performance of the system.

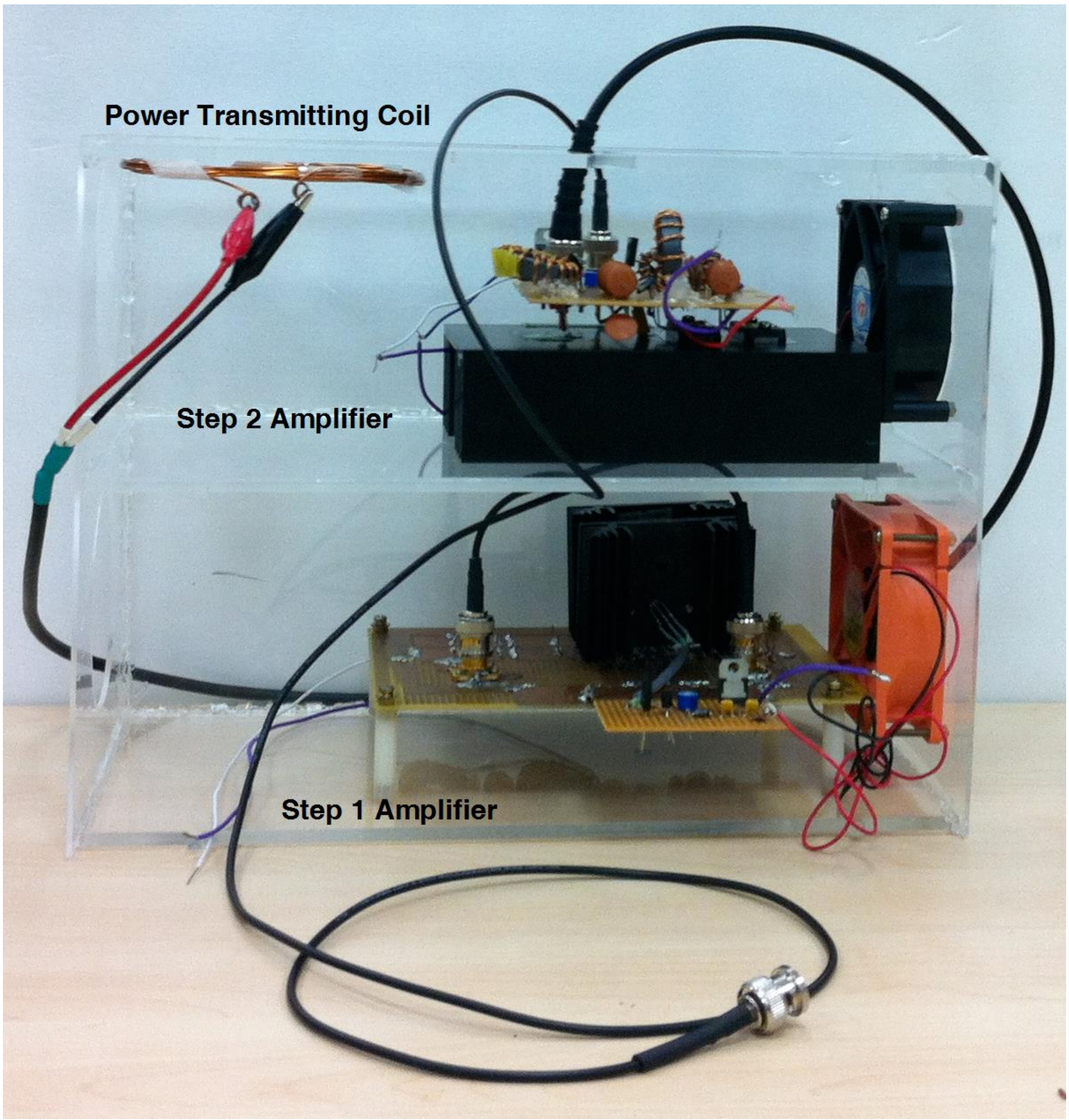


Figure 6.19: Prototype of 2-step power amplifier

This 2-step power amplifier for selective inductive power transferring was then tested. The transmitting coil connected to the output port of the 2-step power amplifier was in a circular shape with the diameter of 10cm comprised of 10 turns of encapsulated copper wire with the diameter of 1mm, as shown in Figure 6.20.

Figure 6.20: Power transmitting coil for 2-step power amplifier

The performance of the 2-step amplifier was tested with the 50-ohm resistor as the output load. As shown in Figure 6.21, the gain of the amplifier increased as the output of the function generator increased, due to the increasing current passed through the power transistors.

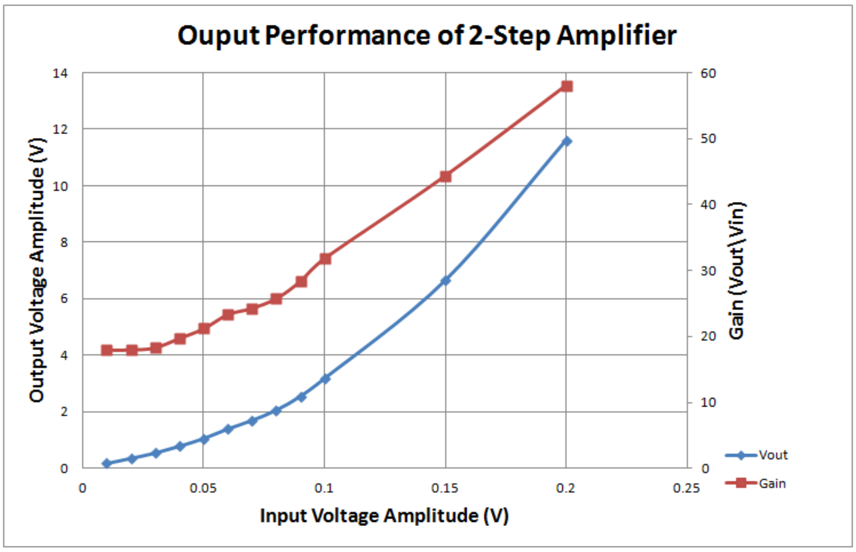


Figure 6.21: The performance of the 2-step power amplifier

With a high gain in power amplification, the system also output waves with less distortion and better stability. Figure 6.22 shows the waveforms of both input and output signals in the frequency of 1.28 MHz. For the power receivers, similar to the LC-based prototype, the coils were 4 cm in diameter and made of 2 turns of 0.5mm diameter enameled copper wire. They were placed 0.5cm above the power transmitting coil in the experiment.

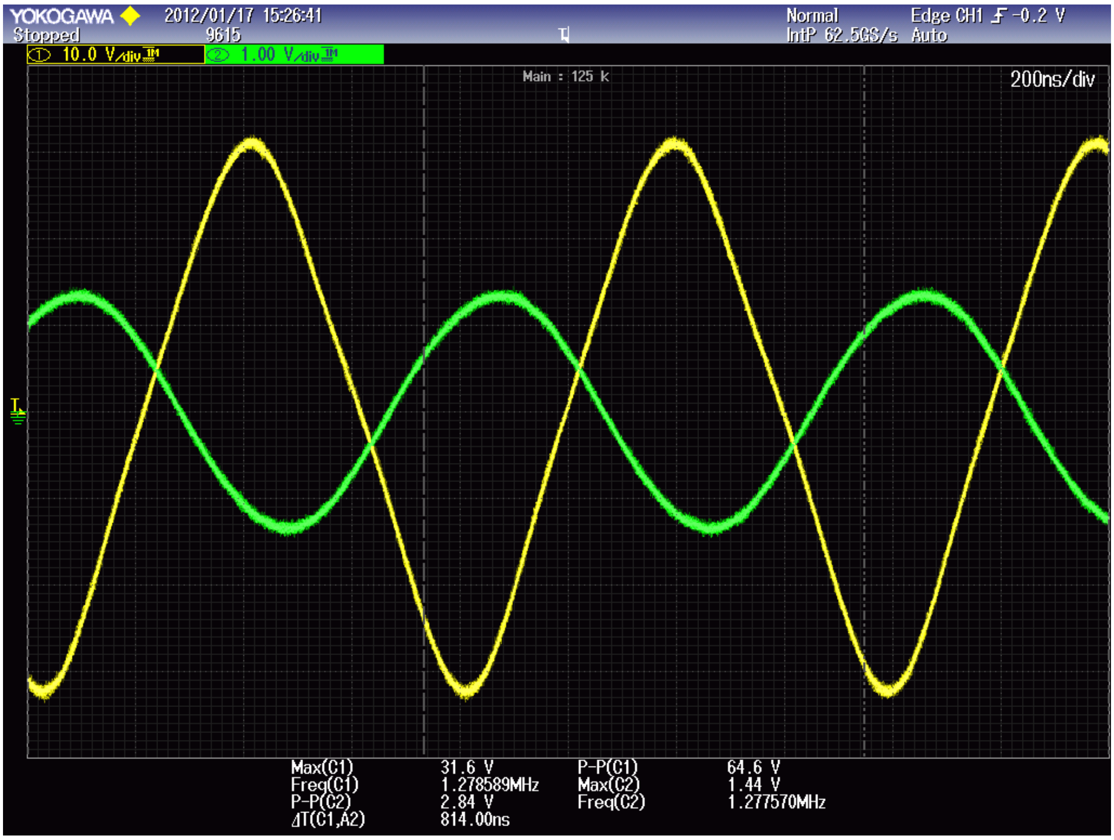


Figure 6.22: Output waveform of the 2-step power amplifier in the frequency of 1.28MHz

I first tested the system performance in the range of lower frequencies from 250 kHz to 1.1 MHz. The capacitors attached to the receiving coils have the value of 68nF, 0.1uF, 0.15uF, 0.22uF, 0.33uF, 0.47uF, and 0.68uF. Figure 6.23 shows that in the prototype of the function generator with RF power amplifier, inductive power can also be transferred to different receivers with different resonant frequencies. Table 6.6 shows the value of the received power for different receivers in different frequencies.

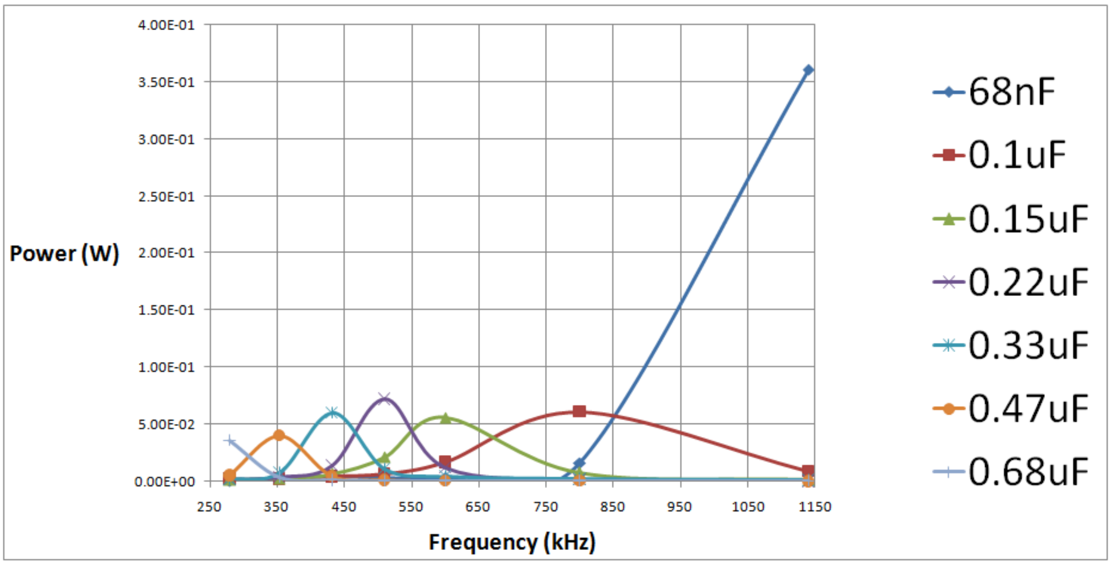


Figure 6.23: The experimental results of RF power amplifier in lower frequencies

Table 6.6: Experimental results of RF power amplifier in lower frequencies, input signal amplitude 0.1V

Capacitance	Resonant Frequency	Peak Voltage	Peak Power
68nF	1.14 MHz	3.8V	3.61E-01W
0.1uF	800 kHz	1.5V	6.08E-02W
0.15uF	600 kHz	1.5V	5.63E-02W
0.22uF	510 kHz	1.7V	7.23 E-02W
0.33uF	432 kHz	1.5V	6.01E-02W
0.47uF	354 kHz	1.3V	4.03E-02W
0.68uF	280 kHz	1.2V	3.60E-02W

As shown in Figure 6.24, in the frequency of 1.14 MHz, the receiver with 68nF received most of the power, and its peak power is much higher than the others. I then tested the system in a set of higher frequencies, ranging from 1 MHz to 2.5 MHz, with the receivers' capacitors of 68nF, 33nF, 22nF, 15nF, and 10nF, as these capacitors could result in higher values of the resonant frequency in the LC model of the power receiver. Similar to Figure 6.23, Figure 6.24 shows a clear separation for the peak power of 68nF, 33nF, and 22nF, while the curves of the receivers with 15nF and 10nF are overlapped with each other. Table 6.7 shows more detailed results of the experiment in higher frequencies.

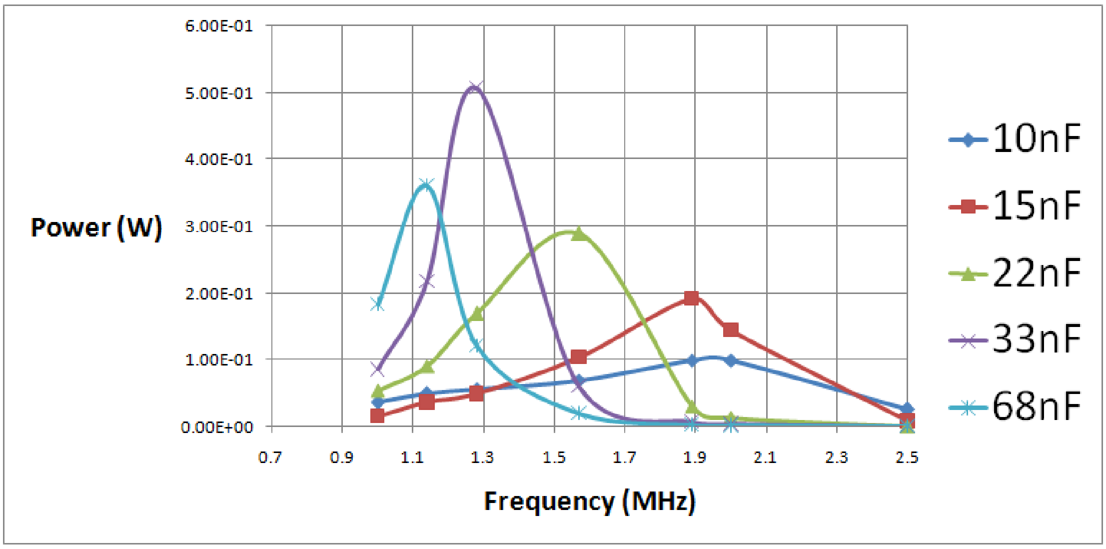


Figure 6.24: The experimental results of RF power amplifier in higher frequencies

Table 6.7: Experimental results of RF power amplifier in higher frequencies, input signal amplitude 0.1V

Capacitance	Resonant Frequency	Peak Voltage	Peak Power
68nF	1.14 MHz	3.8V	0.36W
33nF	1.28 MHz	4.5V	0.50W
22nF	1.57 MHz	3.4V	0.29W
15nF	1.89 MHz	2.77V	0.19W
10nF	2.00 MHz	2V	0.10W

Finally, the 2-step RF power amplifier can take up to 0.5V amplitude input from the function generator, output an amplified signal with the amplitude of 50V, and be able to power up receivers with LEDs separately. In summary, the results of this prototype of power amplifier showed the similar selective results as the first prototype.

6.6 Comparison of Two Prototypes of Selective Inductive Power Transmission

I compare the advantages and disadvantages of both prototypes by exploring the different actuating elements in paper-craft interaction discussed in Table 6.1 and chose a suitable method for TEMPC systems. The comparisons are summarized in Table 6.8.

Table 6.8: Summary of comparison of the two prototypes of SIPT

	Pros	**Cons**
Prototype #1: LC-oscillation circuit	• High efficiency in power transmission (>10%) • Enough power to trigger the movement of shape-memory alloy	• Tuning the frequency with the combination of different values of capacitors. • Limited scale of the values of the frequency
Prototype #2: Signal generator + RF power amplifier	• Accurate value of frequency • Large range of frequencies	• Components heat up easily • Not enough power to activate shape-memory alloy • Requires signal generator which is not easily accessible to end-users.

The first prototype of the oscillation circuit can generate output power up to 60W, and the receivers can efficiently receive inductive power from 5W to 25W with a fairly good efficiency. Therefore, we can use this power to trigger the movement of SMA, as shown in Figure 6.25, which usually requires high power to be activated in high speed and trigger motion of paper. This method could also provide enough power for nichrome wire to reach the temperature for paper-cutting.

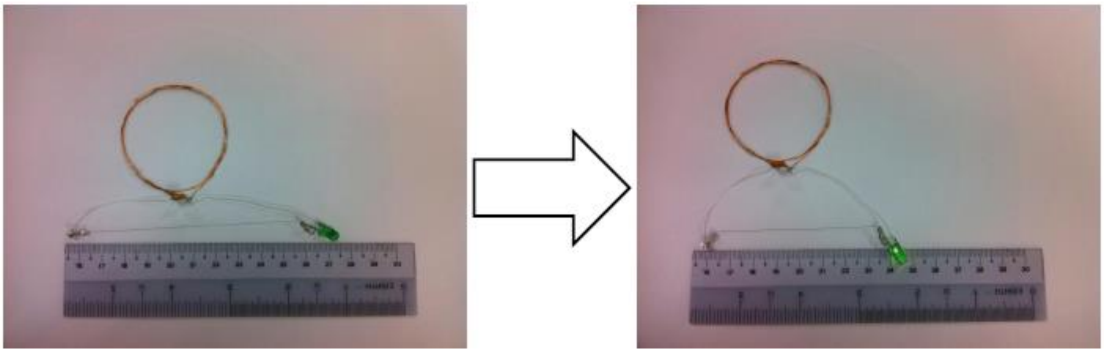


Figure 6.25: Power receiver with SMA

However, this prototype could only produce a small range of low frequencies because of the limited combination of capacitors to match a small set of impedances. In addition, due to the pre-defined values of capacitors, the generated frequency could only be similar to the required resonant frequency instead of the exact value. If more accurate frequencies are needed, more capacitors must be added to the board of the power transmitter, which is limited in size.

For the second prototype using a function generator with RF power amplifier, more accurate and larger range of frequencies can be generated. Therefore, this prototype scales better and can drive more receivers than the first prototype. Based on the datasheet of the power transistors we used, the RF power amplifier could output up to 100W inductive power.

However, we found that the power transistors would be heat up and break even with a small input from the function generator. While using the second prototype to drive SMA, we needed to attach the transistors to a big heat sink and reduce the heat using a fan. Therefore, although the second prototype could provide more accurate resonant frequencies in a wider range, it is hard to transfer substantial power sufficiently. As shown in Figure 6.26, we can use this second prototype to light up LED arrays separately and generate thermochromic display using heating elements, which require less energy than moving with SMA.

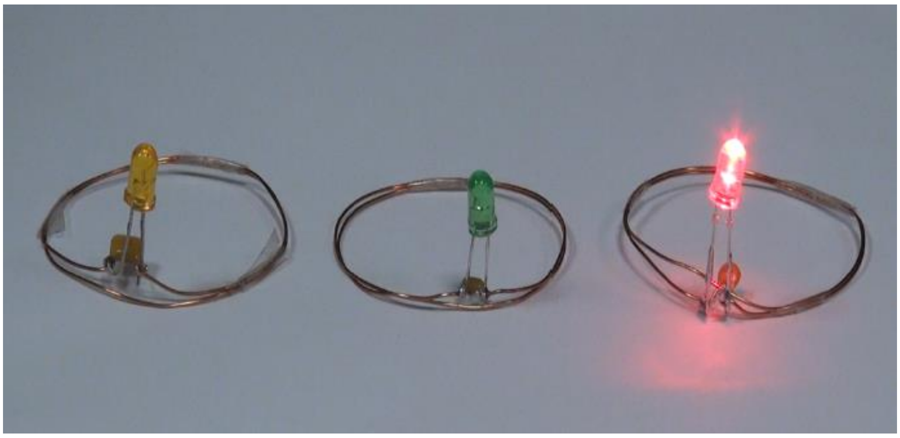


Figure 6.26: Power receivers with LEDs

Summarizing the comparison, we can see the prototype of LC Resonant Oscillator provides better accessibility without requiring special lab devices, and it can generate enough power to activate the physical movement of SMA in paper craft and provide the possibility for developing new interfaces with better controllability.

6.7 Summary

In this section, I introduced the technology of selective inductive power transmission (SIPT), a novel method of inductive power transmission for multiple receivers. It can selectively transfer inductive power to one particular receiver by matching the output frequency of power transmitter with the resonant frequency of each power receiver. Two selective inductive power prototypes were built: an oscillating circuit and a signal generator with RF power amplifier. The experimental results proved the feasibility of selective wireless power transmission. Comparing these two prototypes, I discussed their feasible usage in different contexts of paper crafts and choose the first prototype (LC Resonant Oscillator) as a suitable technology for TEMPC systems.

The technology of selective inductive power transmission simplifies the hardware embedded in paper craft, so it addressed the accessibility problem of hardware-based TEMPC systems. However, it is still not easy to control by end-users as it needs programming to achieve different output frequencies. Therefore, more controllable parameters are needed for TEMPC. This can be tackled by developing new tools based on the technology of selective inductive power transmission. As a result, I developed AutoGami toolkit, a low-cost toolkit with GUI interface to control the technology of selective inductive power transmission for end-users to create automated movable paper craft. Details on AutoGami will be presented in Chapter 7.

Chapter 7 AutoGami: A Toolkit for Constructing Automated Movable Paper Craft[5]

The technical results presented in Chapter 6 demonstrate the possibility of developing an integrated toolkit based on the technology of selective inductive power transmission for designing and implementing automated paper craft. Chapter 7 presents the fourth contribution on TEMPC, AutoGami, which is a toolkit that runs on selective inductive power transmission and allows paper craft to make more types of movements, including folding, bending, linear, and rotary movements. Its graphical interface makes designing and programming easier as it requires little or no engineering knowledge, supports easy trial-and-error testing via simulation, and maintains the accessibility and the tangibility of the automated paper craft safely.

7.1 System Description

7.1.1 Design of AutoGami

Based on the QOC-based design space, we designed the model of AutoGami as shown in Figure 7.1.

[5] Publication:

1. Kening Zhu and Shengdong Zhao. 2013. AutoGami: a low-cost rapid prototyping toolkit for automated movable paper craft. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13). ACM, New York, NY, USA, 661-670.

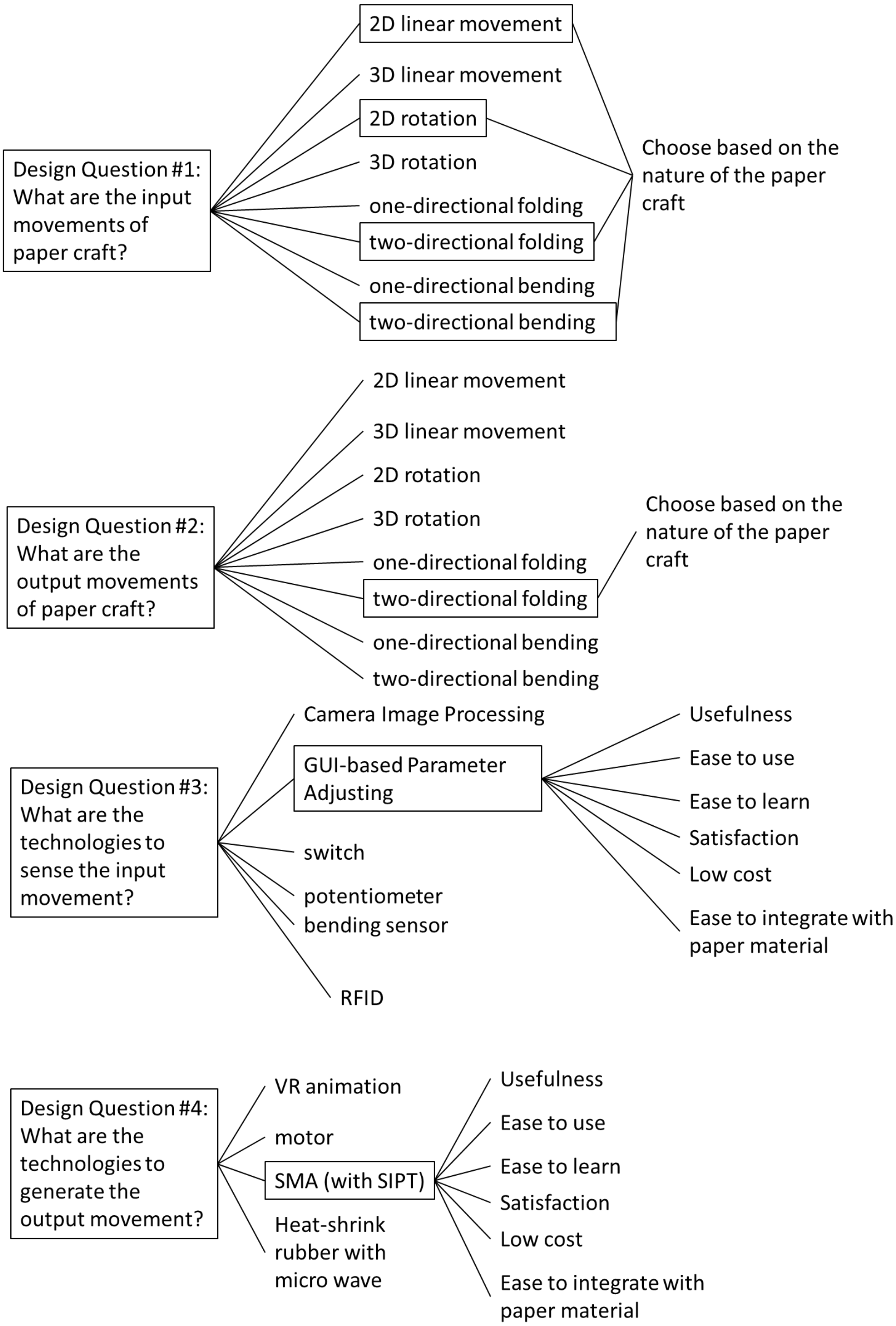


Figure 7.1: QOC-based model of Autogami.

Figure 7.2 shows an overview of the AutoGami toolkit. The AutoGami software supports shape composing and movement planning of the paper craft as well as controls the hardware. The AutoGami hardware is developed based on the technology of selective inductive power transmission, which consists of a controllable power transmitter and power receivers. The inductive power transmitter contains an Arduino processor to control the oscillation generator and the capacitor array to generate alternative electromagnetic field through the transmitting coil. Power receivers in the paper craft are activated according to their resonant frequencies and trigger different movements of the paper craft.

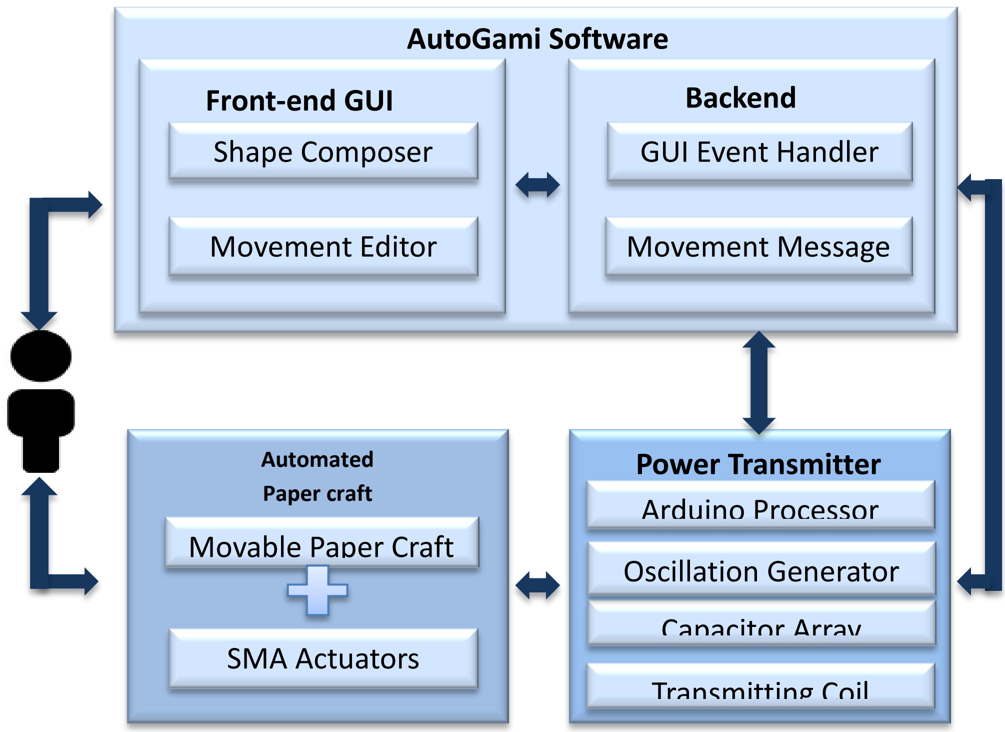


Figure 7.2: Overview of AutoGami's hardware and software

7.1.2 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 7.3, 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 can 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.

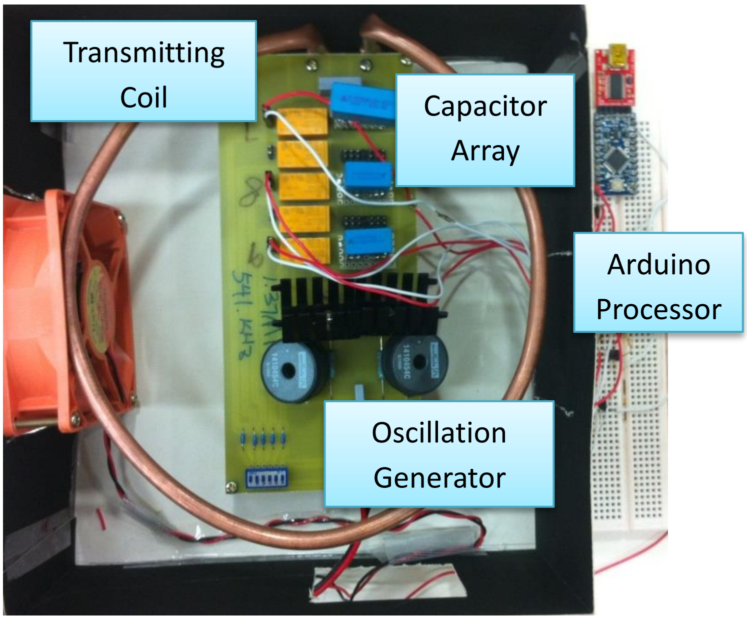


Figure 7.3: Power transmitter of AutoGami

For the structure of the power receiver and movement actuator (Figure 7.4), we used the 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 a diameter of 5cm and has only 2 turns to match the small resistance of the heating wire. The capacitor and the SMA are attached to 2 nodes of the copper coil. Each coil will have a different value capacitor connected, so each will have a different resonance frequency. In addition, each receiver has a unique ID which is mapped to different movements in the design. For the movement actuator, I used spring-shaped SMA with the model of BMX100500 from TOKI Corporation [90].

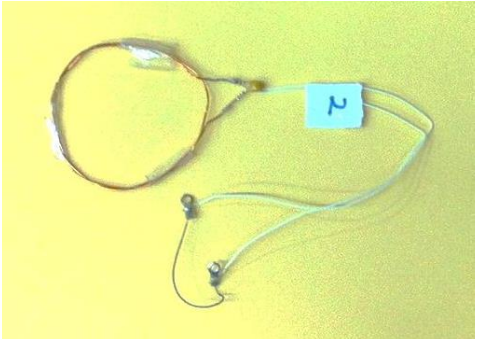


Figure 7.4: Power receiver of AutoGami

7.1.3 Software

AutoGami comes with software (Figure 7.5) that facilitates the design of paper craft movements. Its GUI enables users without programming experience to draw the shape (Figure 7.6a) and plan the movements of the paper craft, assign actuators to the different movements, and set the sequence of those movements. As shown in Figure 7.6b, users can adjust the amplitude and the duration of the movement within the software interface. The software allows the user to simulate movement using SMA before the automated paper craft is implemented in paper and SMA.

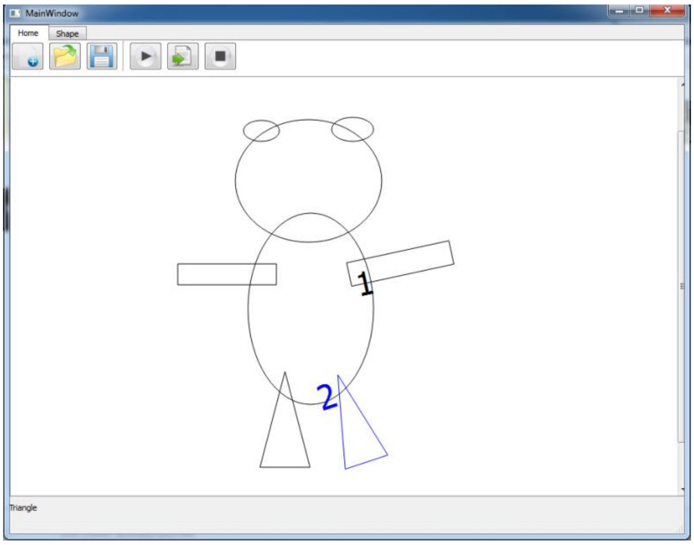
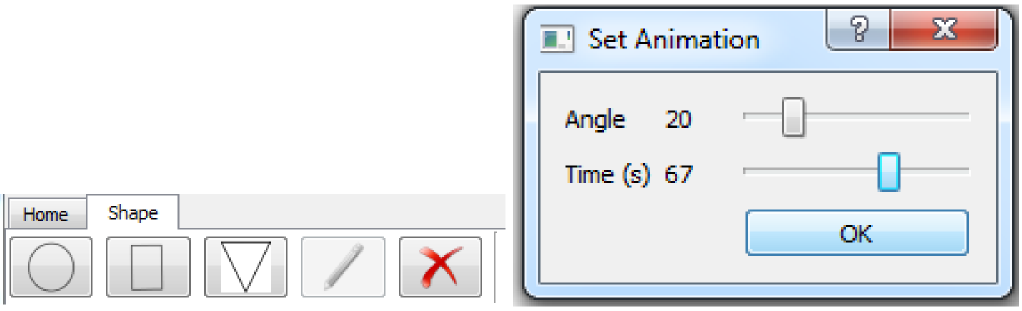


Figure 7.5: Design software interface of AutoGami



(a) (b)

Figure 7.6: AutoGami software functions: (a) drawing tools (b) movement parameters.

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 the motions in the GUI. According to the IDs of the receivers, the user then attaches SMAs to different parts of 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 particular movement in the appropriate output frequency. Figure 7.7 is a step-by-step illustration of this process.

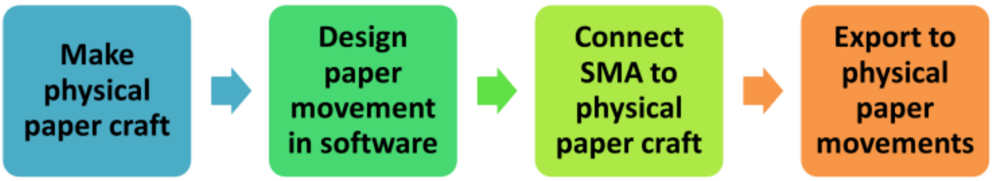


Figure 7.7: Steps of using AutoGami to create automated paper craft

7.2 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.

7.2.1 Basic Features

- Moving different parts of the paper craft separately

Selective inductive power transmission can activate different power receiving coils in different output frequencies. The software allows users to assign a frequency to a movement that will be implemented in a particular part of the paper craft. As shown in Figure 7.8: Mapping between design of paper craft in software and hardware, the IDs of the joints in the drawing are mapped to power receivers with different resonant frequencies so that the user can identify the joint in the paper craft where he/she wants to trigger movement. In the case of the paper bear, the arm can be moved while the leg is static and vice versa.

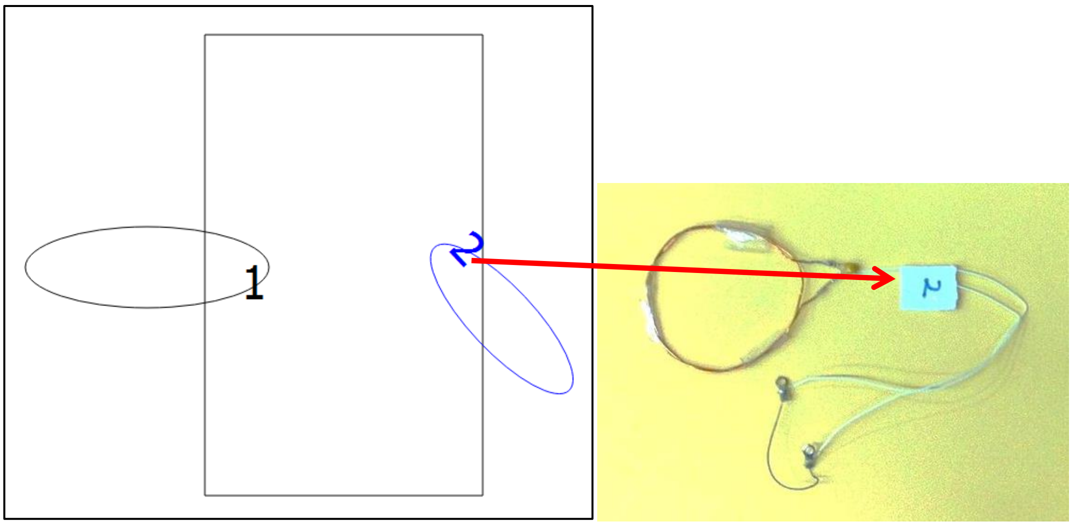


Figure 7.8: Mapping between design of paper craft in software and hardware

- 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 particular distance. In Figure 7.9, slide bars are adjusted to set the amplitude and duration of 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.

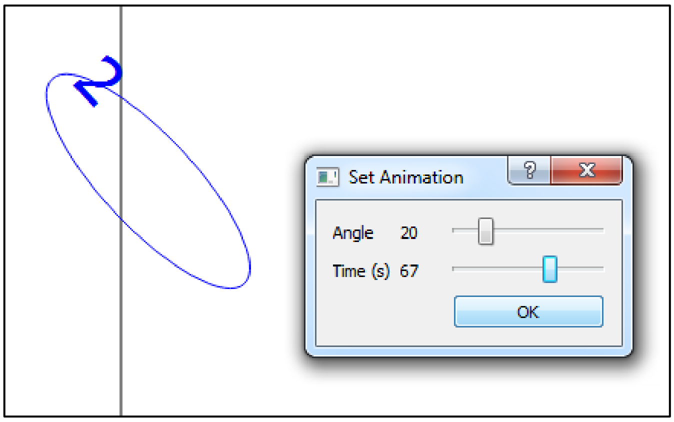


Figure 7.9: Parameter adjustment of paper movement

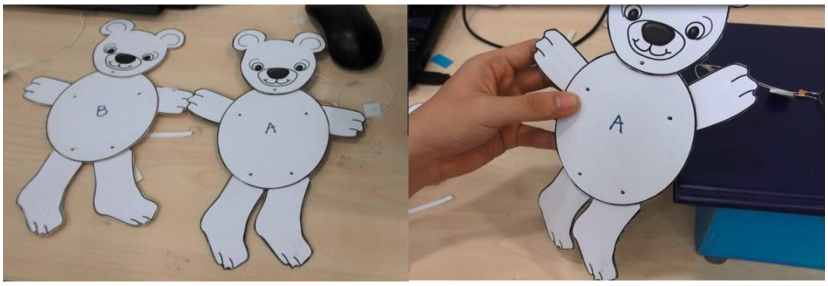
7.2.2 More Advanced Features

- Defining a sequence of movements

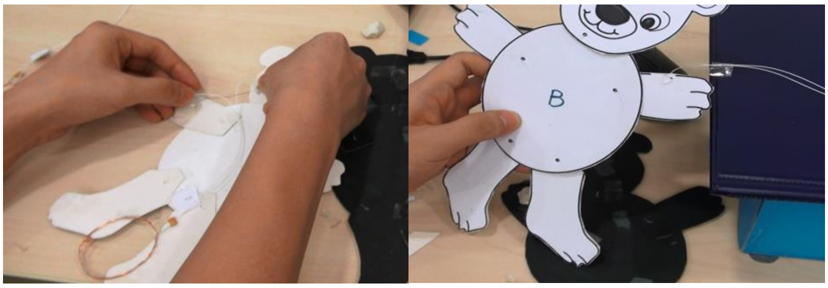
Users can define which movement is played before or after another movement. The sequence of movements can be arranged by setting the parameters of each movement (amplitude and duration) in a particular order. In the example of the paper bear, the user can set a series of movements so that the arm first 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 interface is played to generate the same movements of the original paper craft. The procedure in Figure 7.10 shows that the user only needs to set up the software once to make two or more paper bears execute the same movements.



(a) (b)



(c) (d)

Figure 7.10: Procedure of physically copying automated movement: (a) Two movable paper craft with similar structure, (b) Automated movement in A, (c) Attach the same receiver in B, (d) Generate the same movement in B.

- 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. This results in a new pattern of movement. Figure 7.11 shows the automated directional movements in paper craft.

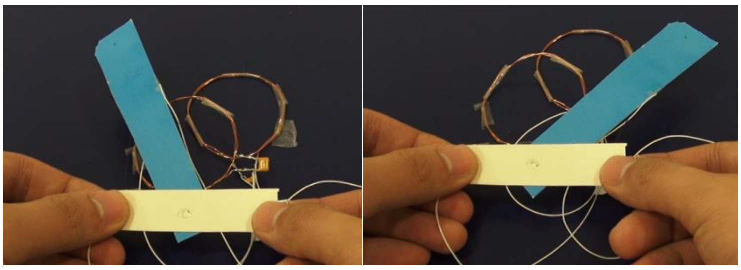


Figure 7.11: Directional movements of automated movable paper craft

7.3 Comparison with Existing Toolkits on Paper Movement

I first compared AutoGami with existing toolkits using the proposed design space (Table 3.1: Design Space of Technology-enhanced Movable Paper Craft) as shown in

Table 7.1, where the dashed line means the or (|) relation among different movements, and the arrow indicates the input-output relationship between two movements.

Table 7.1: Modeling AutoGami in the design space

Not Within Paper					Within Paper				
Rotary Motion		Linear Motion			Bend		Fold		
2D	3D	1D	2D	3D	Single Direction	Multiple Direction	Single Direction	Multiple Direction	
		③	③		③③⑪ ⑤ ④	⑫	⑥ ⑤② ④	⑫	Binary
⑫ ⑬		⑬	⑫ ⑬		⑩ ⑬	⑬	① ⑨ ⑬	⑦⑧ ⑨ ⑬	Continuous

①: Programmable Hinge [102]

②: Interactive Paper Devices [77]

③: Animated Paper [44]

④: Electronic Popables [72]

⑤: Animating Paper with SMA [71]

⑥: Pulp-based Computing [15]

⑦: Oribotics [27]

⑧: Adaptive Bloom [30]

⑨: Programmable matter by folding [32]

⑩: Popapy [103]

⑪: Move-it [70]

⑫: Natural-feature-based Origami Recognition

⑬: AutoGami

It can be observed that AutoGami can cover more cells in the design space to support more features in technology-enhanced movable paper craft, as specified using the semantic model presented in Chapter 3:

AutoGami = (Movement: Rotary, Linear, Fold, Bend,

MovementStyle: Continuous, R: Rotary|Linear|Fold|Bend, W: {})

I then compared AutoGami with other toolkits in terms of expressiveness (customizability), cost, hardware interface, software interface, and prerequisite knowledge from users (see Table 7.2). 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 in AutoGami than other systems and there is less complexity of the hardware embedded in the paper craft.

7.3.1 Cost

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

7.3.2 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 requires expert knowledge in circuit design and programming; and Animating Paper with SMA, which requires soldering skills.

7.3.3 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—unlike 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.

7.3.4 Controllability and Programmability

The expressiveness of a toolkit refers to the extent it allows users to customize various movements, i.e., speed, time, sequence, and direction. 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.

7.3.5 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.

Table 7.2: Comparison of AutoGami and existing methods for automating paper craft using SMA

		AutoGami	Interactive Paper Devices	Animated Paper	Animating Paper with SMA
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

7.4 Workshop Studies

I held five workshops to study the usability of AutoGami, including both quantitative and qualitative, and sought to answer the following questions:

- What is the perceived intuitiveness and learnability of AutoGami?
- Do users find the toolkit useful and engaging?
- Is there evidence that the toolkit facilitates creativity?

7.4.1 Participants

The workshops had a total 10 participants 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 information on each participant's 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 percent of them considered their background of paper craft to be of expert level but their experience in electronics to be at a lower level. The detailed distribution of the participants' backgrounds is shown in Figure 7.12: Distribution of participants' skill on paper craft and Figure 7.13.

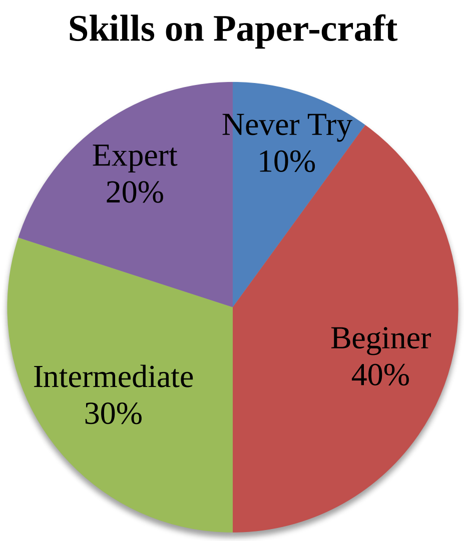


Figure 7.12: Distribution of participants' skill on paper craft

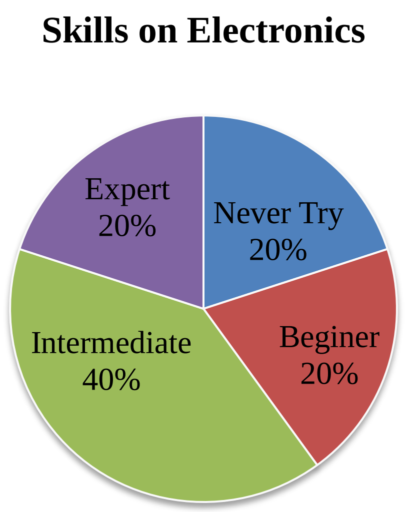


Figure 7.13: Distribution of participants' skill on electronics

7.4.2 Apparatus

As shown in Figure 7.14, 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 software interface installed in a Lenovo ThinkPad X220. They were supplied with tools for making paper craft, such as paper, coloring pens, scissors, needle, and wire. They were also provided with some pre-made paper crafts (Figure 7.15) for reference and inspiration.

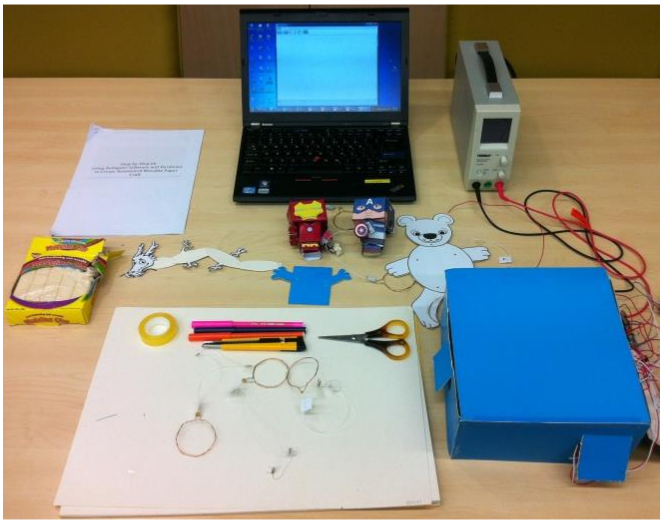


Figure 7.14: Set-up of the workshop environment

Figure 7.15: Pre-made movable paper craft for workshop participants

7.4.3 Method

To study how a toolkit supports creativity, Rubaiat Habib Kazi et al. [74] conducted SandCanvas workshop by first allowing users to use the tool freely and then conducting training tutorials with guided tasks and finally allowing users to finish free tasks. In order to study the creativity-supporting effect of Lilypad [7], Leah Buechley et al. conducted e-textile workshops where firstly they introduced the concept of sewing circuit, followed by showing a few examples, and finally the users were allowed to explore the toolkit by themselves. We adapted methods in SandCanvas [74] and procedures used by Buechley et al. for evaluating systems and tools for art and creativity [7, 74]. 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 (Appendix I) 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. Figure 7.16 shows one group of participants working together during the workshop. After the workshop, the participants answered a questionnaire on their impressions of the toolkit.

Figure 7.16: Participants during workshop

7.4.4 Results

The participants' quantitative and qualitative evaluation of the toolkit, based on three aspects as shown below, was generally positive.

7.4.4.1 Users' Evaluation of AutoGami's Intuitiveness and Learnability

The 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 work with the toolkit. Other participants said, "It is amazing to [familiarize myself] with a new technology and create an automated movable paper craft in less than one hour." They also stated that it can be easily and quickly understood, and that "it is like the LEGO [of paper craft]." The results of the questionnaire showed that intuitiveness received a score of 4.5/5, while learnability scored 3.7/5.

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

7.4.4.2 Users' Opinion on the Toolkit's Usefulness and Capacity to be Engaging

The participants unanimously agreed that the toolkit is useful and that it can be employed in teaching children electronics, software, and interaction design; interactive storytelling; rapid prototyping for robot movements; designing smart furniture; and pure entertainment. In our workshops, several movable paper craft prototypes were created and used to tell animated stories. A mother who participated in the workshop regarded AutoGami as a powerful educational tool which facilitates creativity and trains hands-on crafting ability. This process also teaches simple physics and mechanics. The idea of using AutoGami for rapid prototyping of robots comes from a local social robot design expert. Below is a summary of his comments:

> *Social robot designers often need to experiment with novel dimension from the anthropomorphism point of view. This involves experimenting with the combination of facial expressions and body gestures. Simulating such effects on 2D displays is insufficient and loses the environmental context. As a user study typically requires several alternative prototypes to explore the design space, developing them is a time consuming and expensive process. AutoGami provides a new lightweight layer between software (2D and 3D) design and physical robot prototype. It is cost effective, flexible, and expressive enough to simulate many interesting behaviors of social robots.*

The smart home application is recommended by interior designers, many of whom wanted to use AutoGami for rapid prototyping of smart homes and furniture. One designer specifically asked to use AutoGami to simulate the lighting in a home model. By connecting the receiving coils with LEDs at different locations, he can experiment with when, where, and how bright each light appears in the home model.

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) compared to the guided task (4.2/5).

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

7.4.4.3 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, animals, cartoon characters, and architecture. Figure 7.17 shows the paper craft of a boat sailing in the sea, created by an animation designer and an electronic engineer. They 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.

Figure 7.17: Automated movable boat model

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, as shown in Figure 7.18. They then mimicked a conversation between these two paper characters.

Figure 7.18: Paper characters with facial movements

A group of two Chinese engineering students, one male and one female, downloaded a template of a cartoon character and animated it through the AutoGami software. As shown in Figure 7.19, the character is able to wave both of his arms and kick both legs, with the hinges at the center of the body.

Figure 7.19: Automated cartoon character

The group comprised of a Sri Lankan male and a Chinese female moved the 2D movement in AutoGami to 3D space. As shown in Figure 7.20, they created a 3D model of a house, attached the power receiver to the hinge of the door, and animated the door opening and closing in a 3D form.

Figure 7.20: 3D model of house with movable door

Similarly, one group of robotic hobbyists created a 3D paper model of a robot and automated arm-waving movements through AutoGami, as shown in Figure 7.21.

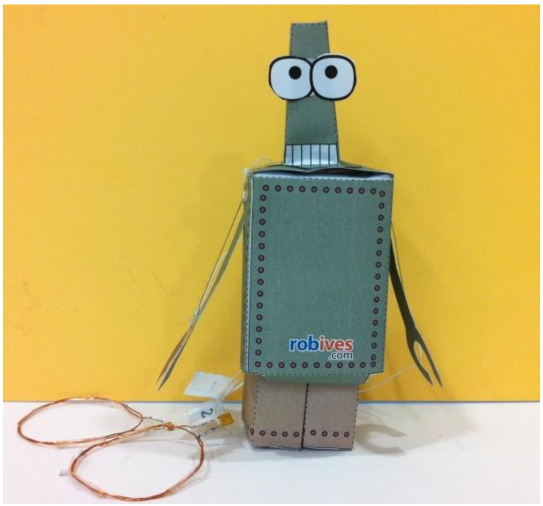


Figure 7.21: Automated movable robot model

Last but not least, another group of participants created a dog paper craft, as shown in Figure 7.22. It is able to shake its tail and move the head automatically to mimic the behavior of barking.

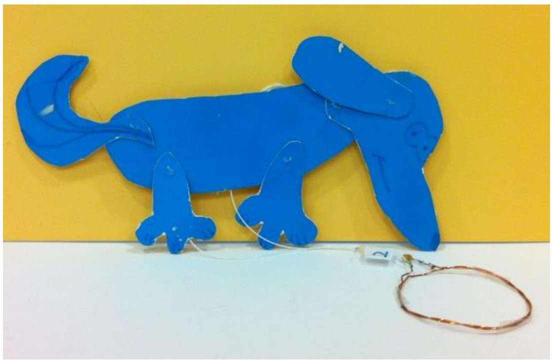


Figure 7.22: Automated movable dog model

The post-workshop questionnaire also shows positive results in this. The participants said the toolkit *allows 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* had a score of 4.4/5.

In summary, the distribution of the scores for selected key questions are illustrated in Figure 7.23. Details of the quantitative results are shown in Appendix H.

Figure 7.23: Score distribution for selected questions in the post-workshop questionnaire

7.4.5 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 as well as in further development of the toolkit.

7.5 Usage Scenario

The AutoGami toolkit has been demonstrated on many occasions besides the 5 workshops discussed, including a 2-day local MakerFair, a 3-day interior design exhibition, a 1-day open house exhibition, and 2 peer laboratory visits. Although AutoGami has limitations that prevent it from performing very complex and precise movements, the feedback from over 400 people has provided strong evidence towards serious uses of AutoGami. Inspired by the examples of the automated paper craft created in these events (as described in Section 7.4.4.3), I designed the following usage scenarios to demonstrate the real-world applications of AutoGami.

7.5.1 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.

However, 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 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 7.24) and then uses AutoGami's software and hardware to design simple movements. 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 Tortoise as it moves and clapping 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.

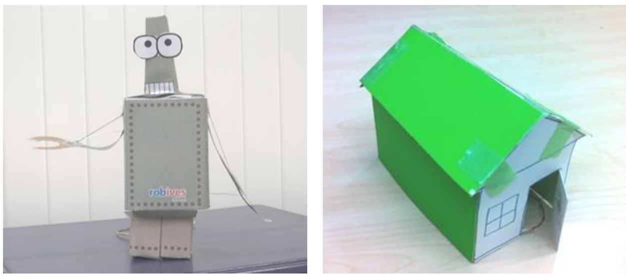
Figure 7.24: Movable paper characters for telling the story *The Hare and The Tortoise* using AutoGami

7.5.2 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, looks and feel. The movements he needs to design range from saying greetings, nodding and shaking the head, 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 7.25a, he uses AutoGami to design movements, test their various forms, 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 particular types of movement appropriate for each robot, which in turn allowed him to determine the most suitable hardware to support each 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 7.25b). 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 desired intelligent behavior and for communicating ideas with his colleagues.



(a) (b)

Figure 7.25: (a) Robot prototyping using AutoGami; (b) Smart home prototyping using AutoGami

7.5.3 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 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.

These three scenarios highlight the main features of AutoGami and illustrate how the toolkit can help enrich people's daily lives and improve their efficiency at work.

7.6 Summary

In summary, AutoGami is 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 development of AutoGami provides a solution for the research question on the toolkit for technology-enhanced movable paper craft. The results of workshops prove the usefulness of AutoGami, as users can create diverse, meaningful automated paper craft using the toolkit. In addition, participants felt highly engaged in using AutoGami to create automated paper craft. AutoGami provides a unique platform with rich capability, controllability, and expressiveness, and can support various possible applications of automated paper craft, such as storytelling, artwork design, and product prototyping, etc.

Chapter 8 Conclusion & Future Work

This thesis investigated the study of paper computing, especially technology-enhanced movable paper craft (TEMPC). By surveying the existing efforts in this area, I identified three main problems in the current TEMPC research, and my PhD research contributed to tackling these problems by answering four research questions, as shown in Table 8.1.

Table 8.1: Contributions towards tackling three problems in TEMPC

Problem	Question	Contribution
Diversity of Movements	What are the possible movements that can be enhanced by technology?	Taxonomy (QOC Design Space & Semantic Model)
Accessibility of tools for end-users	How should the technology support users to explore different types of movements?	Origami Tower, Snap-n-Fold, Selective Inductive Power Transmission
	What is the nature of a general toolkit that is easy to learn and use?	AutoGami
Controllability of movements	What are the controllable parameters in TEMPC?	AutoGami

1. What are the possible movements that can be enhanced by technology?

In Chapter 3, I presented the taxonomy consisting of QOC design space and semantic model. The QOC design space provides a method of modeling TEMPC systems, which reflects how TEMPC systems fulfill the design criteria in details. The semantic model summarized all the existing TEMPC systems in one table view and clearly revealed the missed space in the taxonomy. The analysis suggested most of current TEMPC toolkits focused on a single type of movement with only binary control, requiring specific set-up. Therefore, the taxonomy analysis motivated the development of new TEMPC systems.

2. How should the technology support users to explore TEMPC?

In order to explore the taxonomy of TEMPC, I developed two systems for sensing and generating movable paper craft. On sensing movable paper craft as input, the method of natural-feature-based origami recognition (Chapter 4) allows users to fold a piece of paper, such as postcards or a cut-out from newspaper, to input and control digital content, such as gaming. On the other hand, Snap-n-Fold (Chapter 5) converts the skeleton structure of a real-world object into the folding pattern of an origami base and generates virtual animation output. The user studies of these two systems suggested that users preferred more controllability and tangibility in TEMPC systems with better usability.

These lessons drove me to develop the technology of selective inductive power transmission for TEMPC. It allows users to embedded electronic actuators into paper craft without concerning about the circuit design for controlling the hardware. This technology simplifies the creation of technology-enhanced movable paper craft and provides the potential for a general toolkit with more controllability.

3. What is the nature of a general toolkit that is easy to learn and use?

4. What are the controllable parameters in TEMPC?

To address these two questions, I developed the AutoGami toolkit (Chapter 7), which integrates GUI-control interface with the technology of selective inductive power transmission, allowing end-users to create automated movable paper craft in a low-cost and easy way. Workshops for using AutoGami have proven its usefulness, as users can create diverse, meaningful automated paper craft using the toolkit. Therefore, the AutoGami toolkit contributed to tackling the three problems in TEMPC by supporting more types of movements with more controllability and better accessibility.

In conclusion, the main contributions — the taxonomy, the technologies, and the toolkit — open a unique platform with rich capability, controllability, and expressiveness, and can support various possible applications of technology-enhanced movable paper craft, such as storytelling, artwork design, and product prototyping, etc. This thesis can be taken as an initiative in promoting do-it-yourself (DIY) culture in technology-enhanced paper craft. For the future work with these efforts done in my PhD study, I would like to continue investigation in technology-enhanced movable paper craft and expand this research to a bigger venue, technology-enhanced handicraft.

- *Publicize the AutoGami toolkit*

Through the 5-year research of technology-enhanced paper craft, especially the development of the AutoGami toolkit, I see this as a starting point for me to investigate, develop, and support a DIY culture in technology-enhanced paper craft. I envision this direction similar in spirit to the Lego robotic kit and the e-textile culture promoted by Leah Buechley, and I have performed several actions, such as public demonstrations and workshops, for the realization of this goal. The toolkit was well-accepted by audience members in these workshops.

To further support users of AutoGami and hobbyists of technology-enhanced paper craft, I plan to develop a website to facilitate the exchange of ideas, designs, programs, and construction tips. Other practical steps toward sparking this community might include organizing regional electronic fashion shows with prizes awarded to especially dazzling designs. In addition, with permission for using the user data from this website, I would like to analyze the trend of this TEMPC culture, as a sub-culture of the Maker Movement.

- *General technology-enhanced paper craft*

While movable paper craft is an important branch under the umbrella of the art of paper craft, there are still other types of paper artwork, such as paper cutting, paper gluing, paper drawing, etc. They are not only a form of fun and entertainment but also prove to have positive benefits in education and other more serious applications. I would like to further investigate other types of paper craft, study the general design space of technology-enhanced paper craft, and expand the AutoGami toolkit to facilitate normal users to create their own technology-enhanced paper craft.

- *General technology-enhanced handicraft*

As the DIY Maker Movement is one of the main trends in the 21st century and handicraft is an important part of DIY culture, I envision a future where every hobbyist in handicraft is able to easily integrate interactive computing technology into their artworks, such as interactive clay, interactive textile, and interactive wood-carving, etc. The tools on crafting, software programming, and hardware tinkering will be intuitive for them to learn and use, just like AutoGami. This is already happening with the popularization of the 3D printer and open source hardware platforms such as Arduino. Thus, I would like to take the lead in collaborating with handicraft artists and researchers in this area to study the theory of handicraft interaction, to explore the technology to support handicraft interaction, and invent new tools for creating more interesting, useful, and relevant interactive handicraft.

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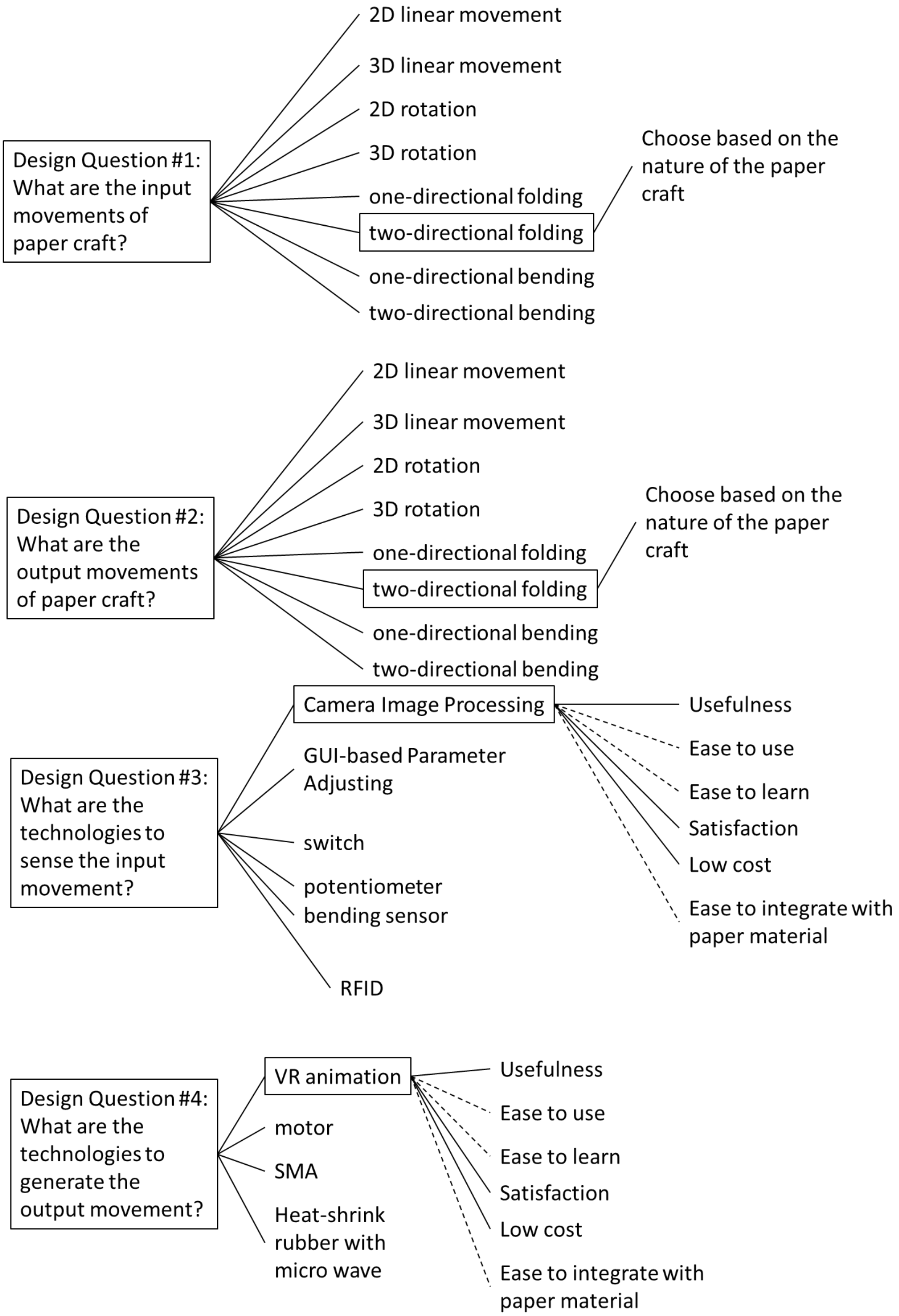
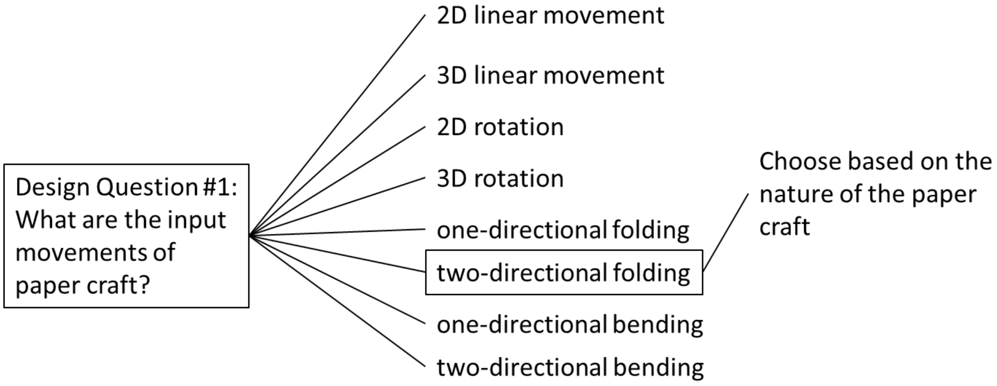
DOI=10.1007/978-3-642-34292-9_29 http://dx.doi.org/10.1007/978-3-642-34292-9_29.

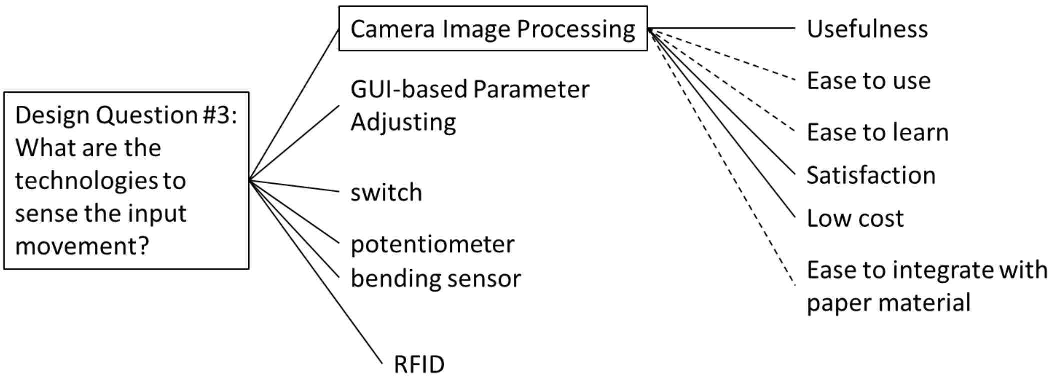
Appendix A: QOC-based Visualization of Existing TEMPC Projects

1. Recognition of Folding Process from Origami Drill Books (Section 2.1.1)

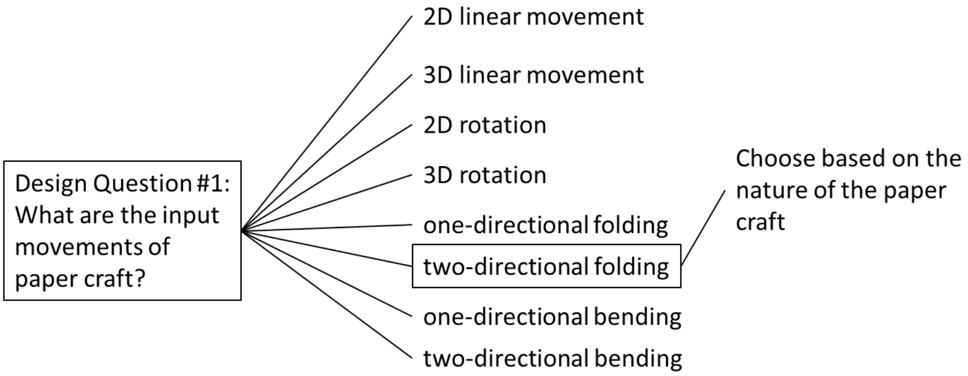


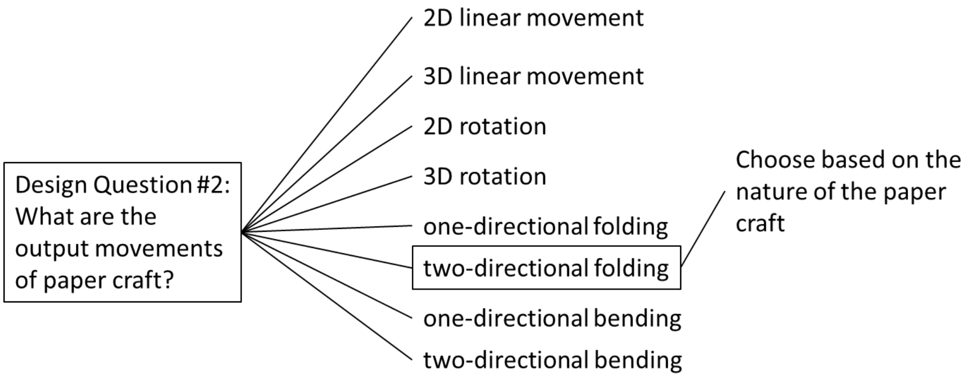
2. Estimation of Folding Operations Using Silhouette Model (Section 2.1.2)

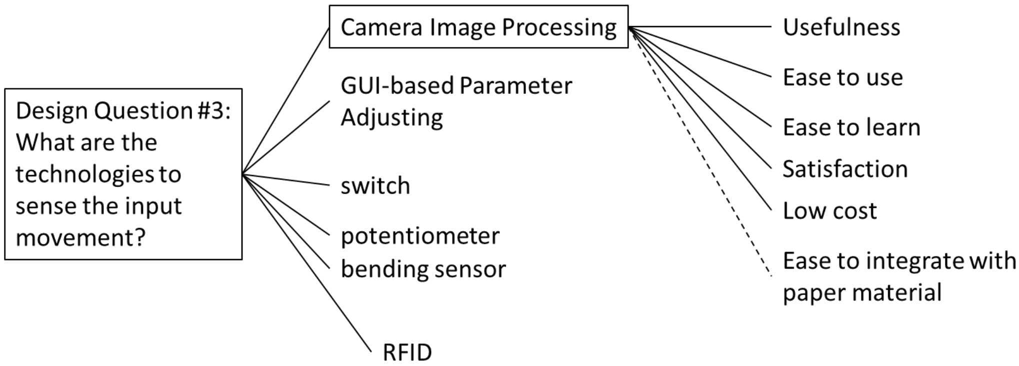


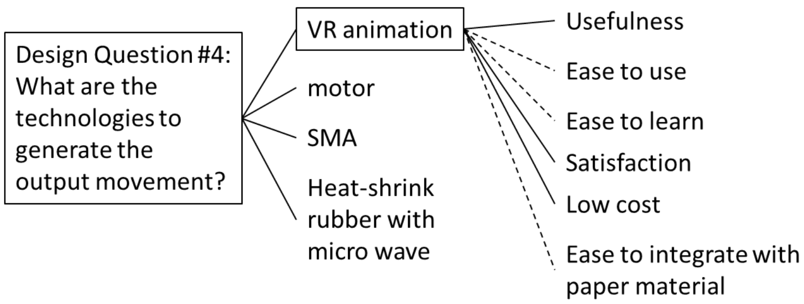


3. Recognition and modeling of paper folding configuration using 2d bar code (Section 2.1.3)

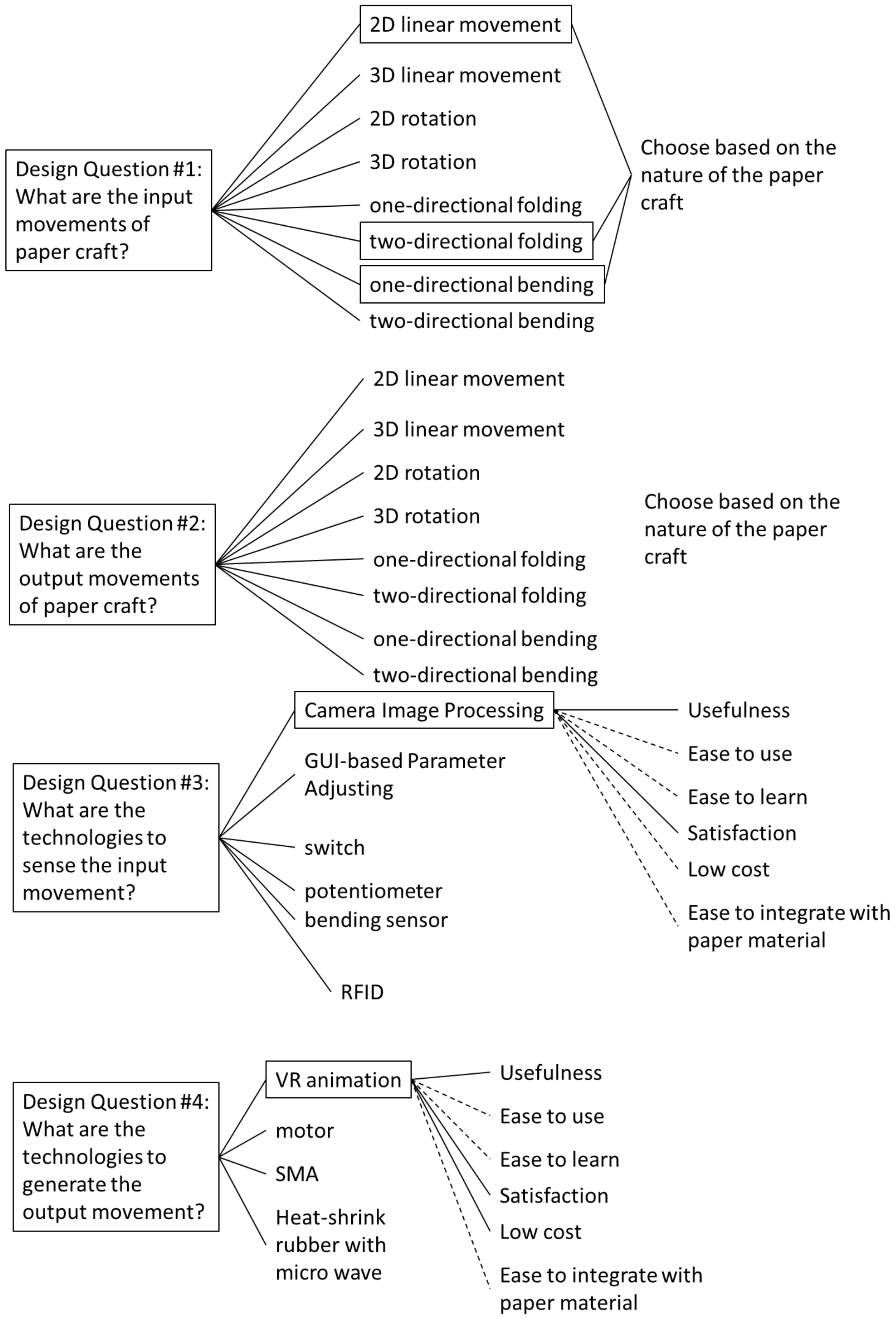




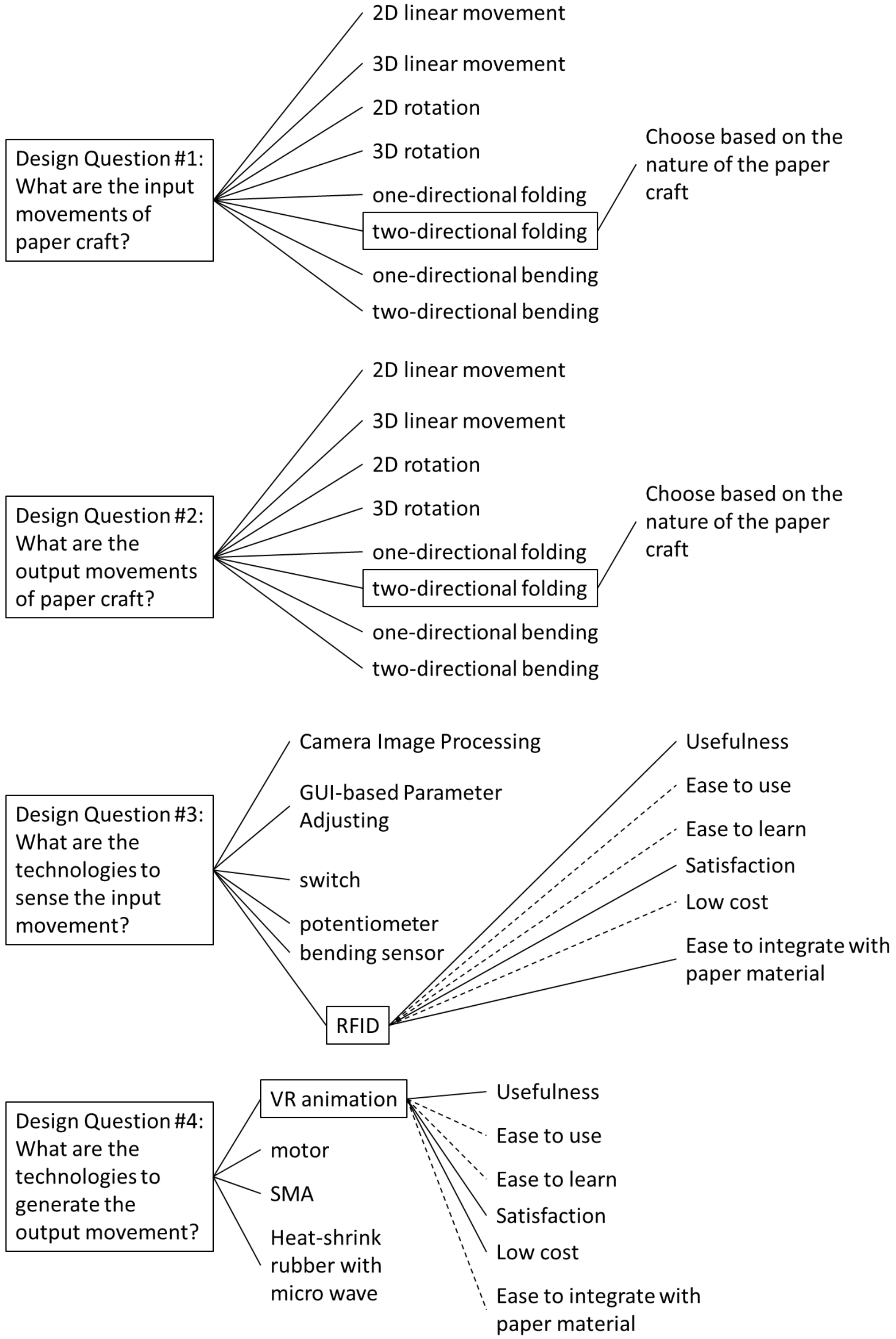




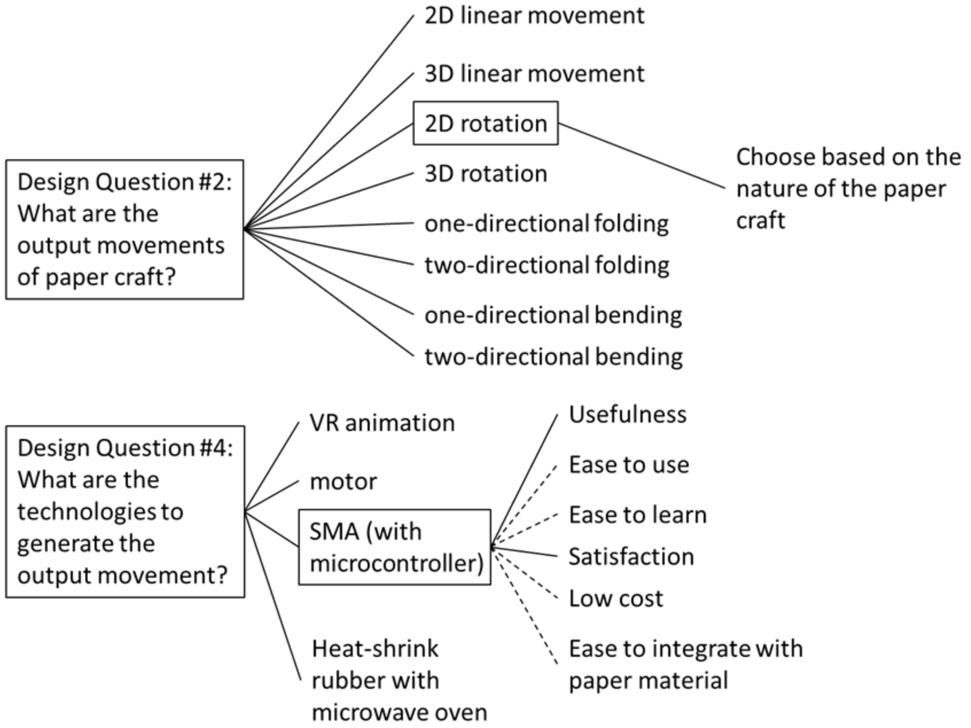
4. Foldable User Interface (Section 2.1.4)



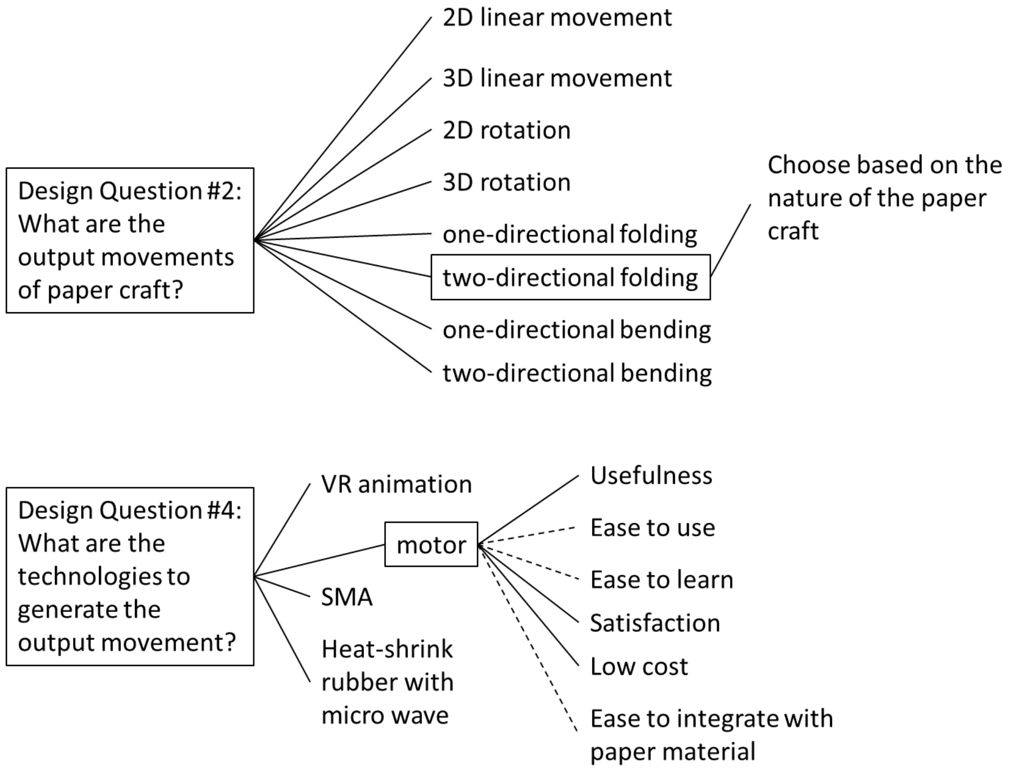
5. Origami Desk (Section 2.1.5)



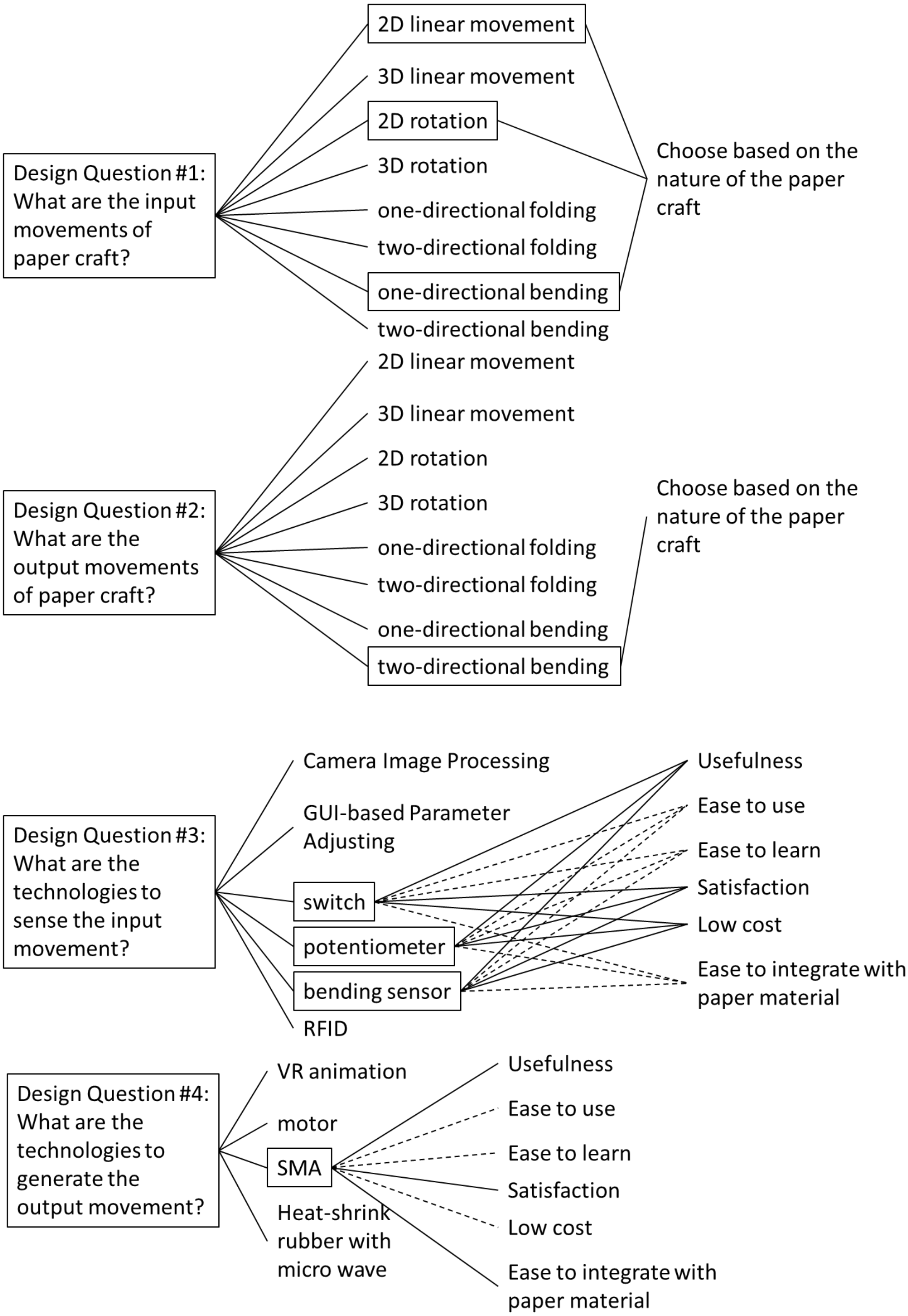
6. Programmable Hinge (Section 2.1.6)



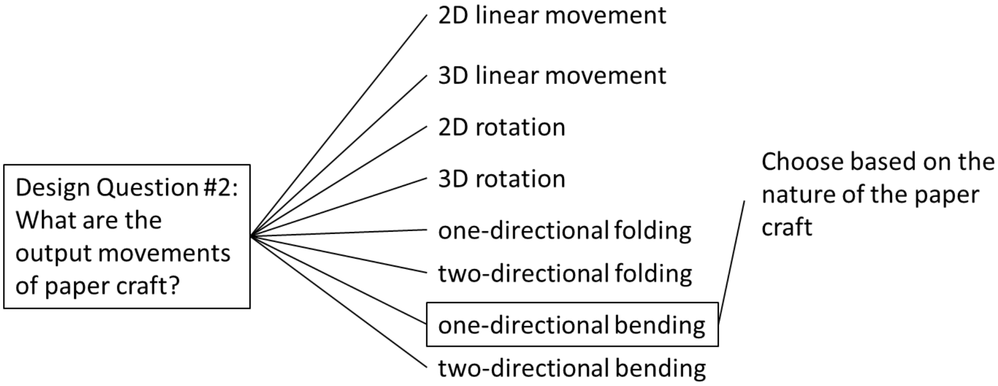
7. Oribotics & Adaptive Blooms (Section 2.1.7)

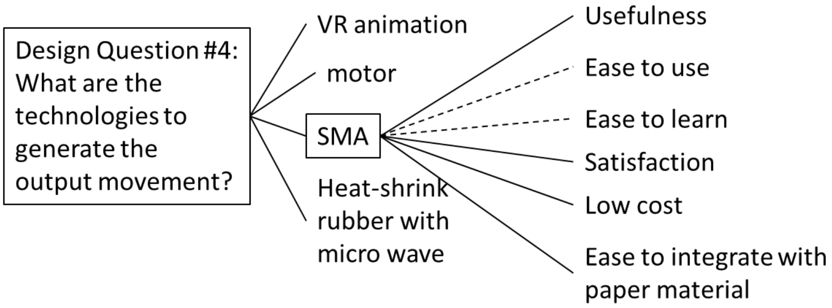


8. Electronic Popables (Section 2.1.8)

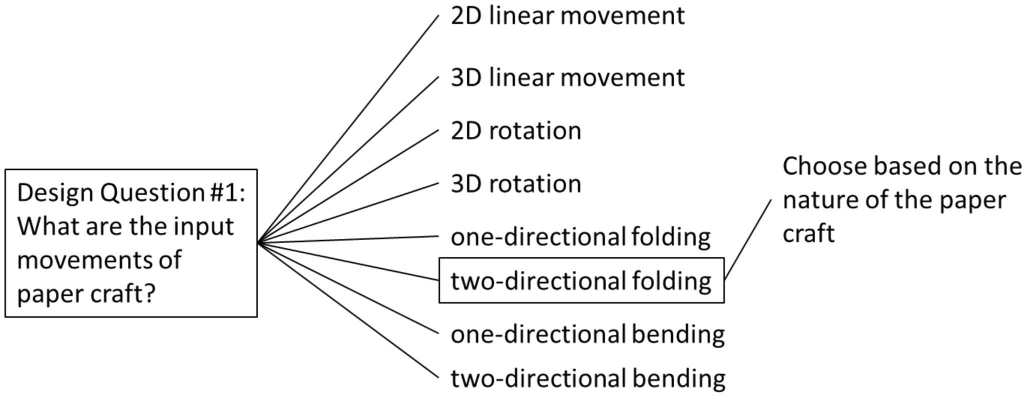


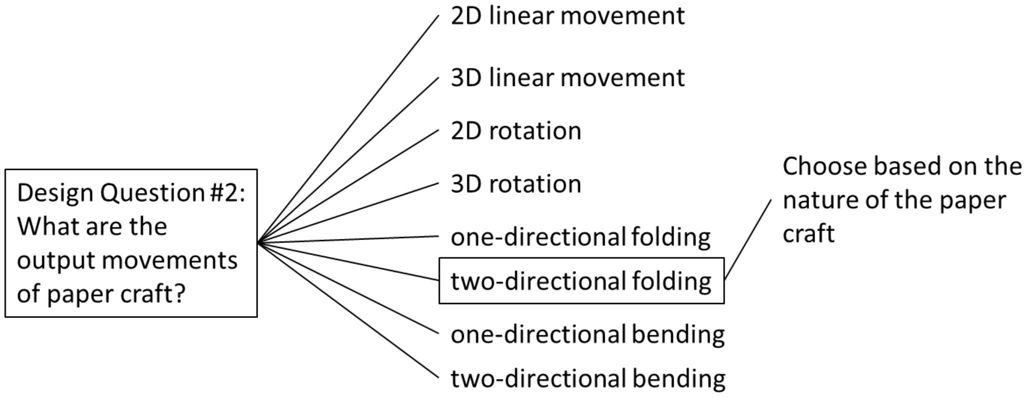
9. Move-it (Section 2.1.9)

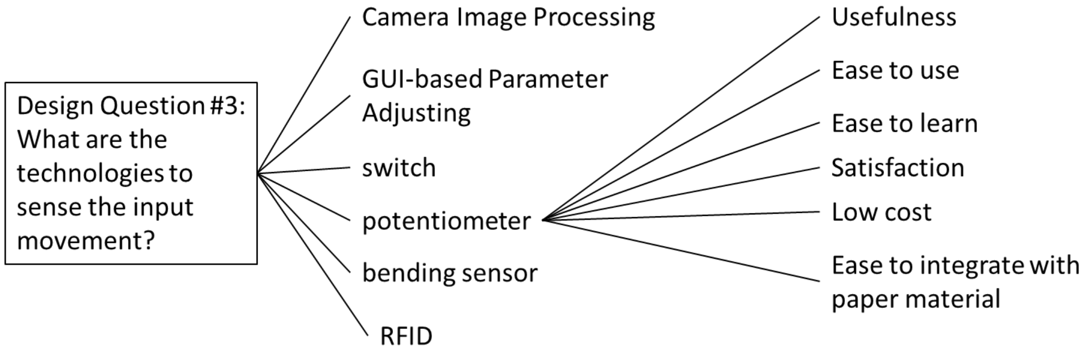


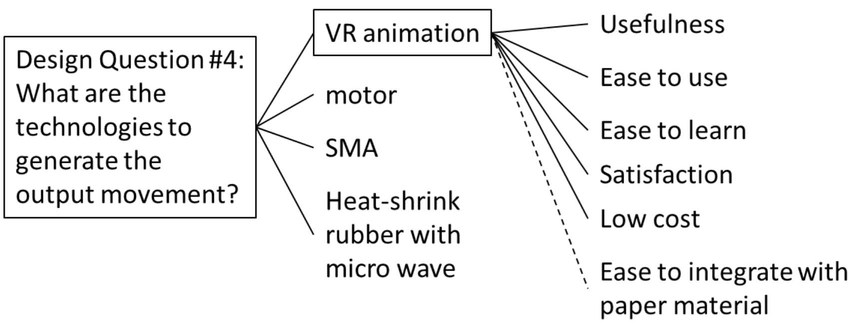


10. Easigami (Section 2.2.1)

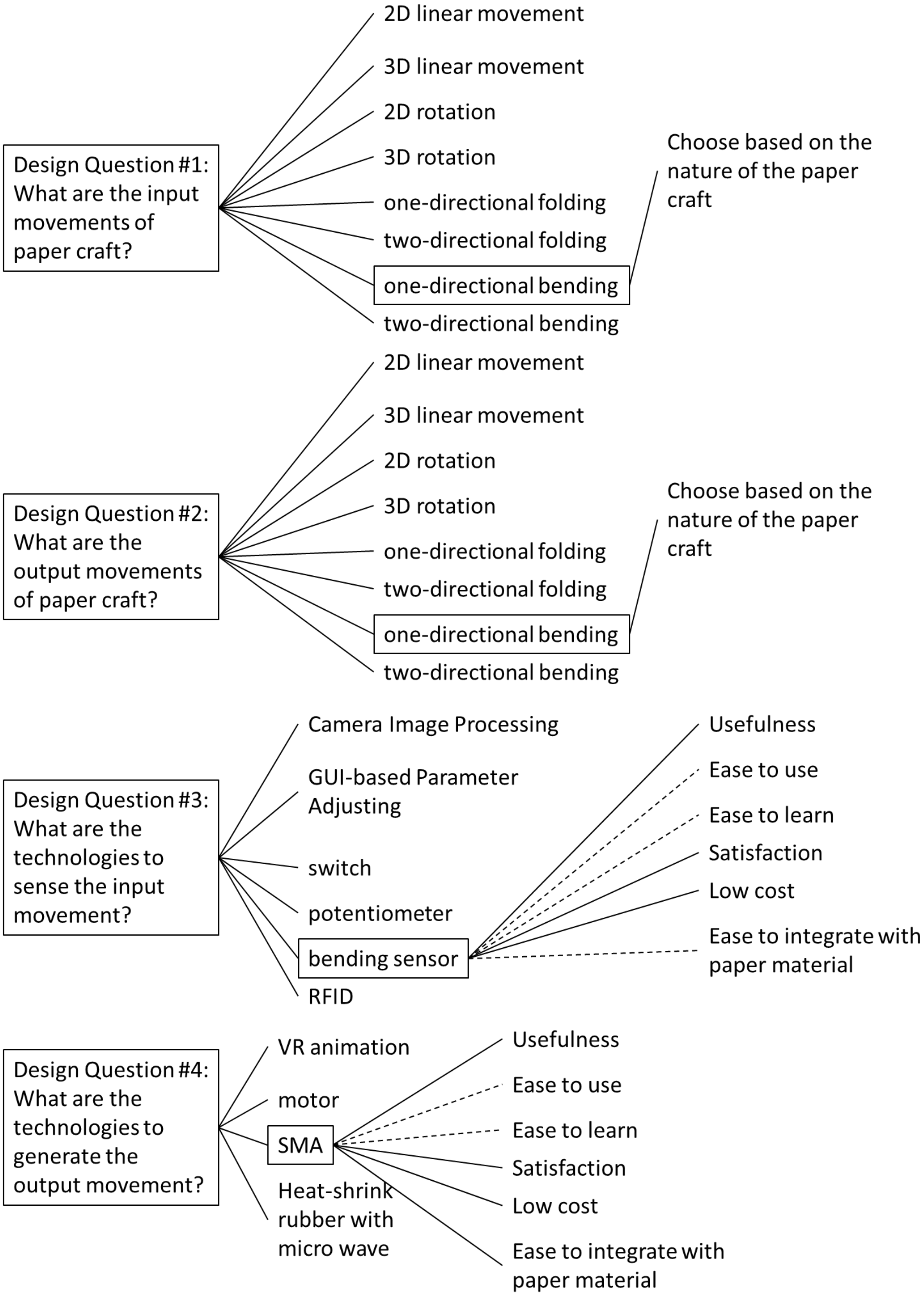




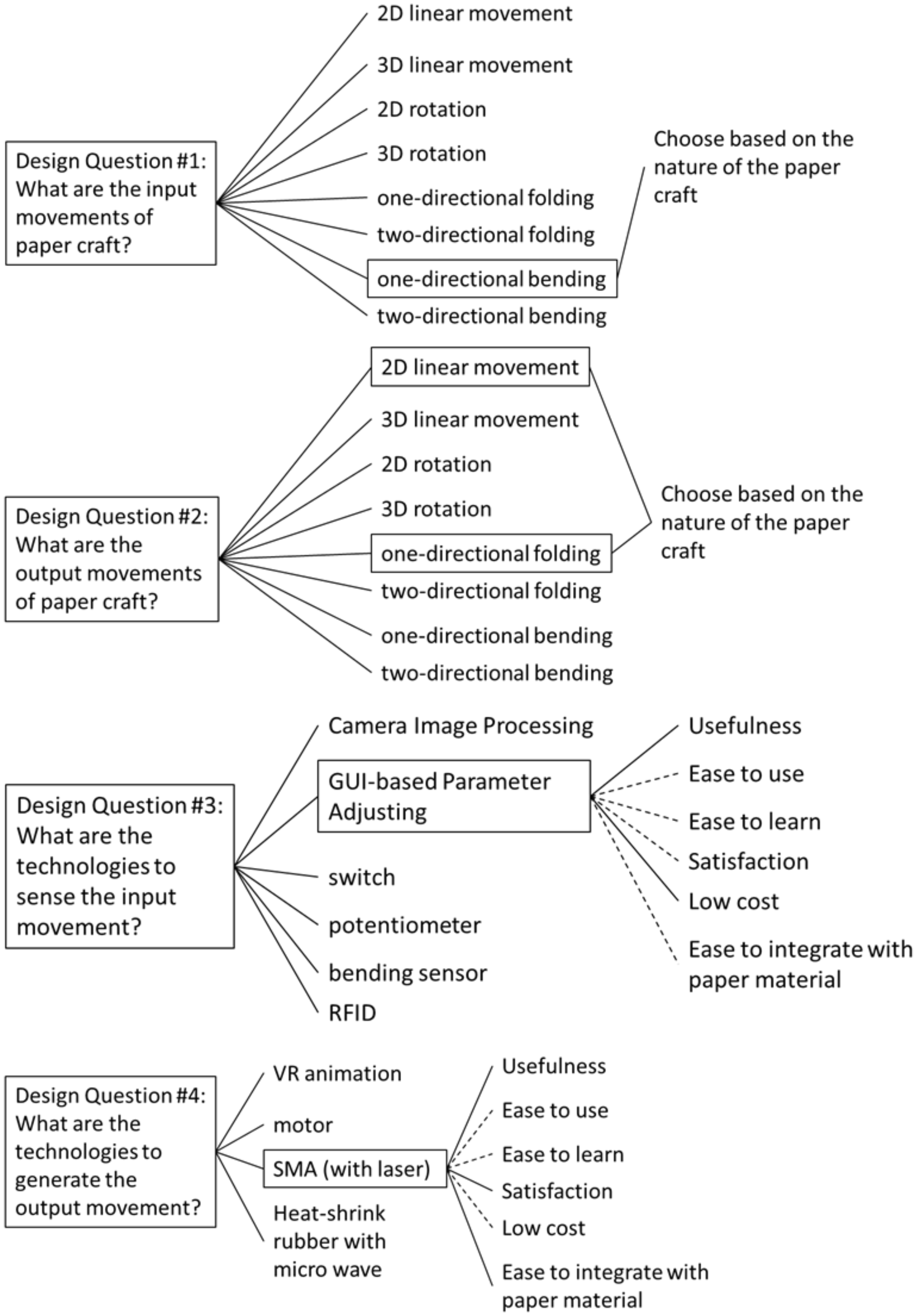




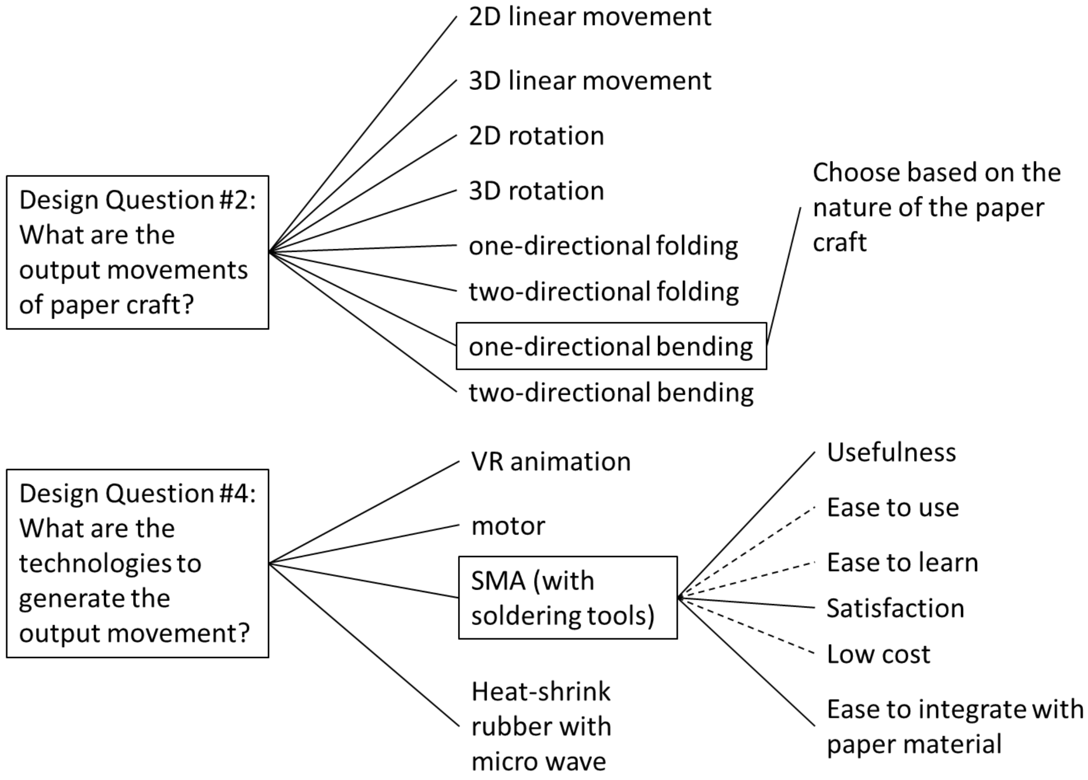
11. Pulp-based Computing (Section 2.2.2)



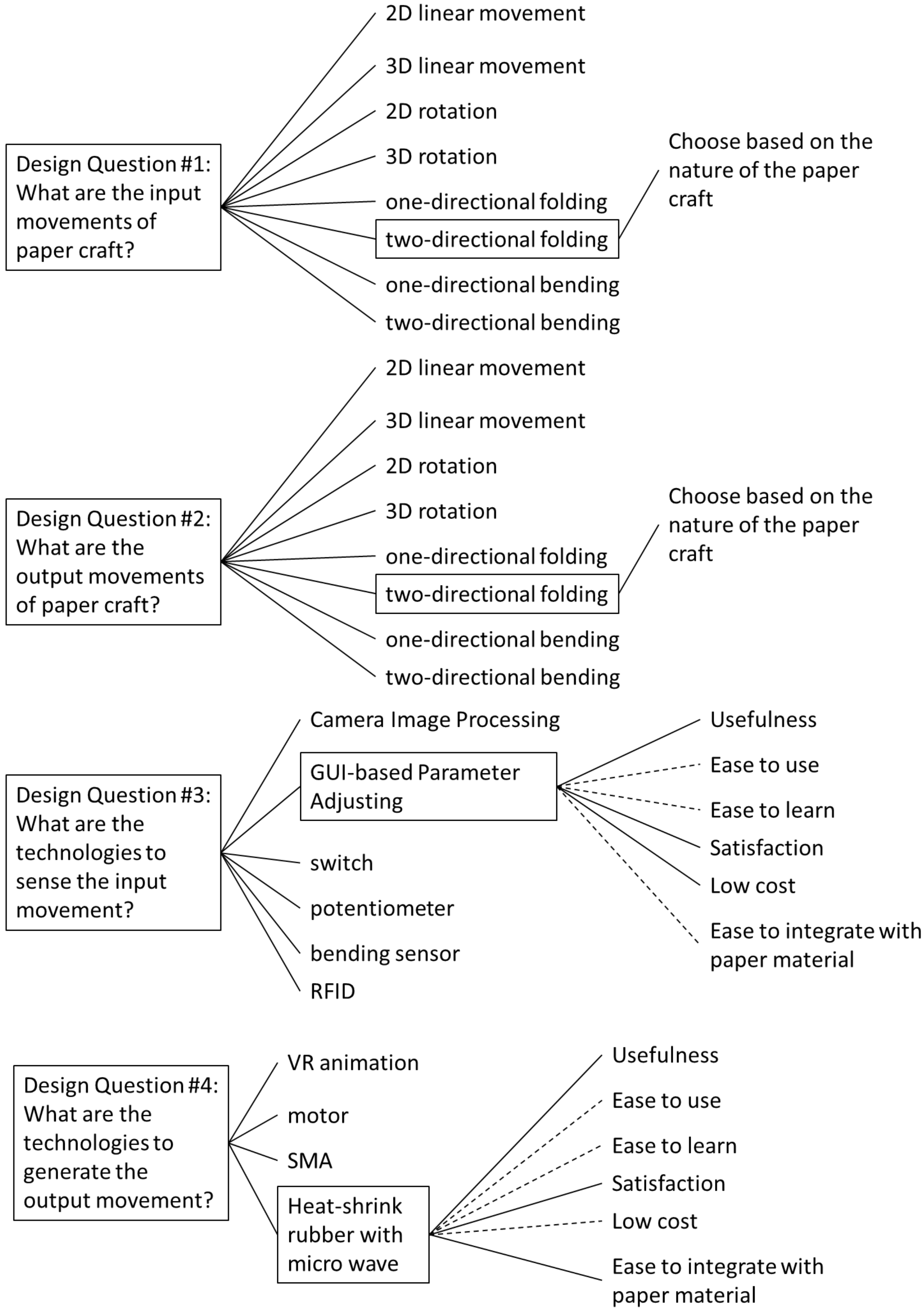
12. Animated Paper (Section 2.2.3)



13. Animating Paper with Shape-memory Alloy (Section 2.2.4)



14. Popapy (Section 2.2.5)



Appendix B: Questionnaire on Origami Tower

User study on Origami Tower

Thank you very much for participating in this workshop. I hope you enjoyed to play the tower game with origami. Here are some questions about your experience in this activity. Your answers would help us understand and improve our research better.

* Required

Gender * _______

Age * ______

Prerequisite Skill: Paper-craft *

What is your previous experience of creating paper-craft, such as origami, paper pop-up?

Never try □ Beginner □ Intermediate □ Expert □

- Ease of Learning: How do you think of learning to use origami to paper this game?

- **The tutorial is clear for me to learn how to play the game. ***

Strongly Disagree 1 2 3 4 5 Strongly Agree

- **It is easy for me to learn to play the game with origami. ***

Strongly Disagree 1 2 3 4 5 Strongly Agree

- Ease of Use: How do you think of playing Origami Tower?

- **It is easy to set up the game-play environment. ***

Strongly Disagree 1 2 3 4 5 Strongly Agree

- **It is easy to use paper to move in the game. ***

Strongly Disagree 1 2 3 4 5 Strongly Agree

- **It is easy to fold the paper and build a tower in the game. ***

Strongly Disagree 1 2 3 4 5 Strongly Agree

- **It is easy to win the game using origami. ***

Strongly Disagree 1 2 3 4 5 Strongly Agree

- Usefulness: How do you think of the functionality of this technology?

- **The technology with webcam is useful for turning my origami into towers in the game ***

Strongly Disagree 1 2 3 4 5 Strongly Agree

- **The game works well when I want to move in the game. ***

Strongly Disagree 1 2 3 4 5 Strongly Agree

- Satisfaction: How is your experience of playing Origami Tower?

- **Playing game with Origami is more fun than using keyboard and mouse. ***

Strongly Disagree 1 2 3 4 5 Strongly Agree

- **Playing game with keyboard and mouse is more fun than using origami. ***

Strongly Disagree 1 2 3 4 5 Strongly Agree

- **I would like to use computer with origami more and more in the future. ***

Strongly Disagree 1 2 3 4 5 Strongly Agree

- **I would recommend it to my friends. ***

Strongly Disagree 1 2 3 4 5 Strongly Agree

- Cost of Origami Tower

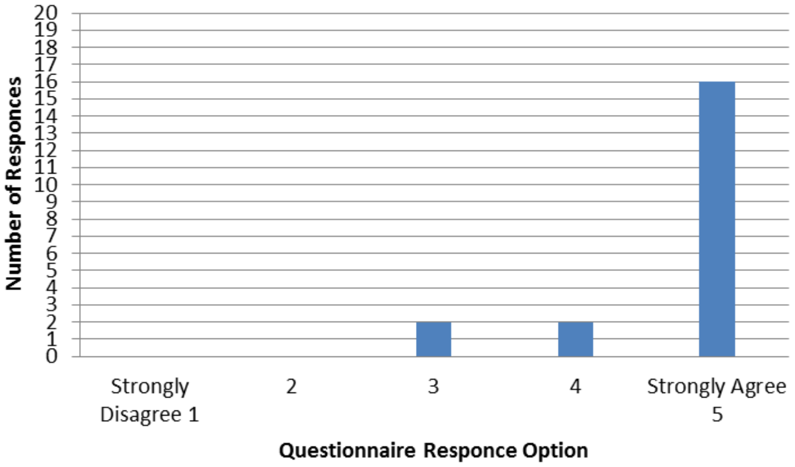
- **I am willing to pay for it. ***

Strongly Disagree 1 2 3 4 5 Strongly Agree

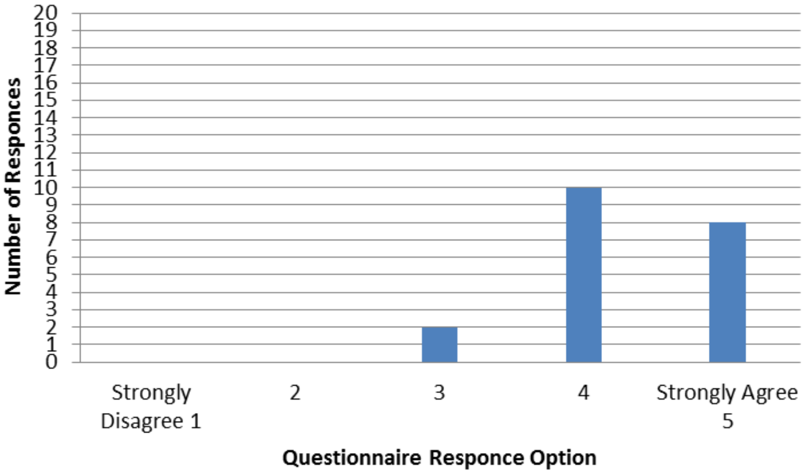
Appendix C: Detailed Distribution of the Results of Questionnaire for Origami Tower

- Ease of Learning: How do you think of learning to use origami to paper this game?

- **The tutorial is clear for me to learn how to play the game. ***

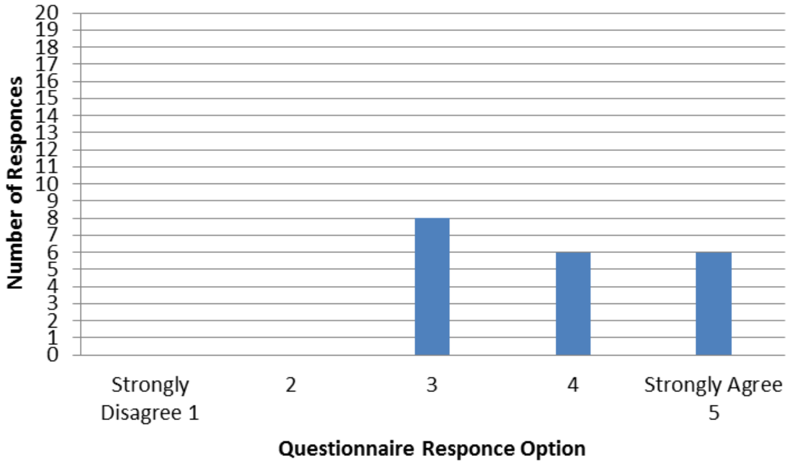


- **It is easy for me to learn to play the game with origami. ***

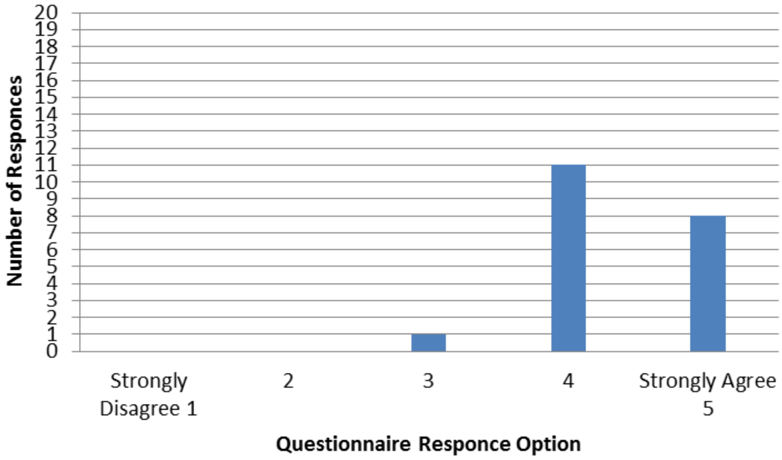


- Ease of Use: How do you think of playing Origami Tower?

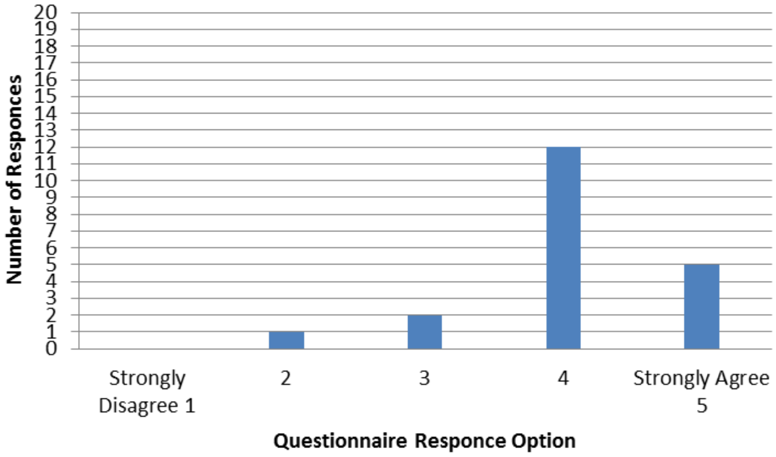
- **It is easy to set up the game-play environment. ***



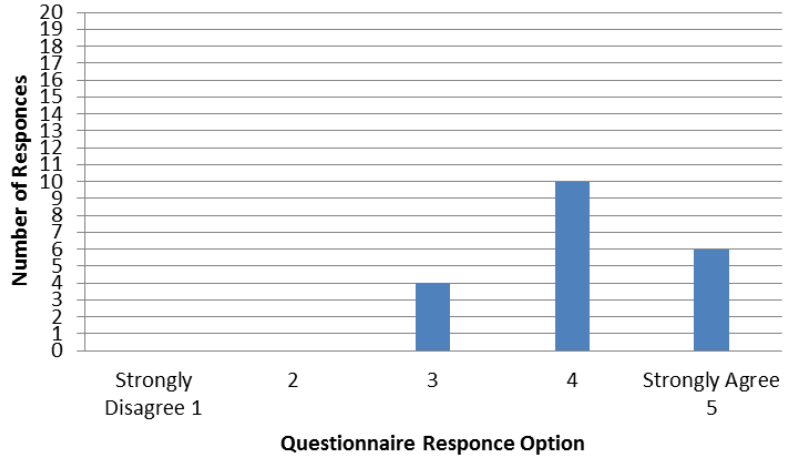
- **It is easy to use paper to move in the game. ***



- **It is easy to fold the paper and build a tower in the game. ***

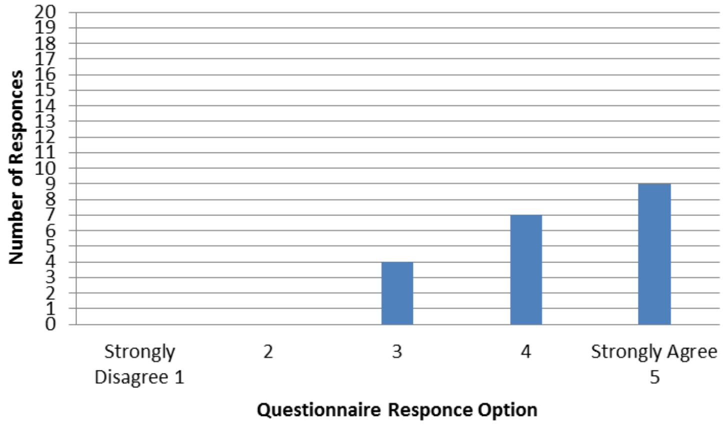


- **It is easy to win the game using origami. ***

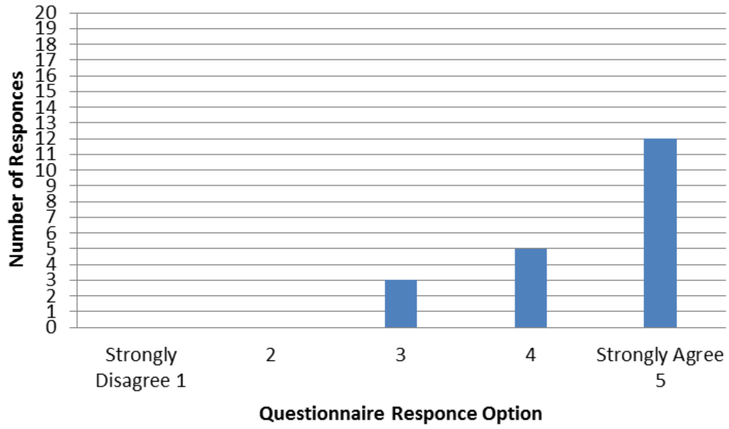


- Usefulness: How do you think of the functionality of this technology?

- **The technology with webcam is useful for turning my origami into towers in the game ***

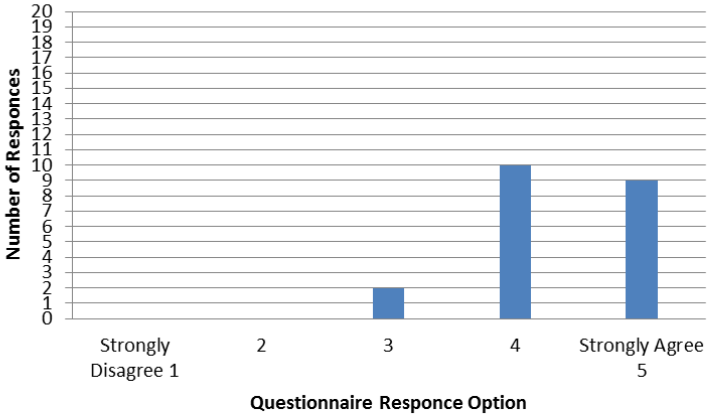


- **The game works well when I want to move in the game. ***

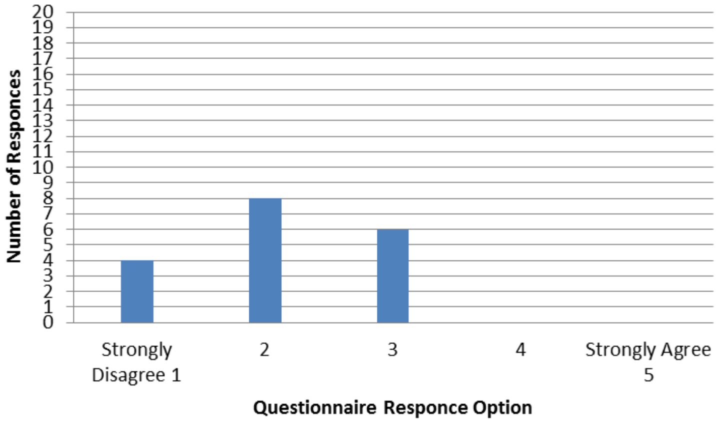


- Satisfaction: How is your experience of playing Origami Tower?

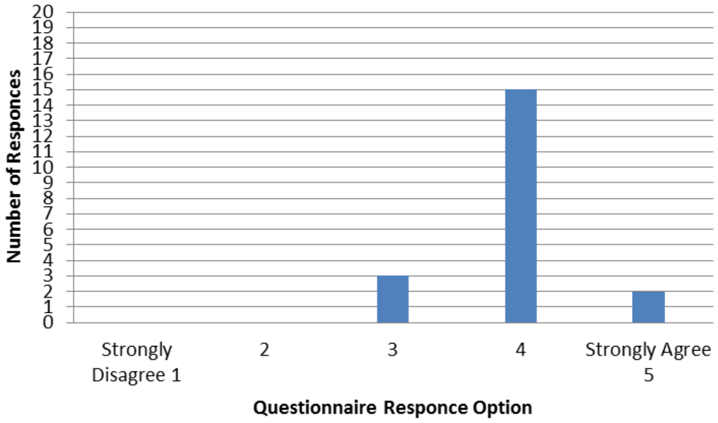
- **Playing game with Origami is more fun than using keyboard and mouse. ***



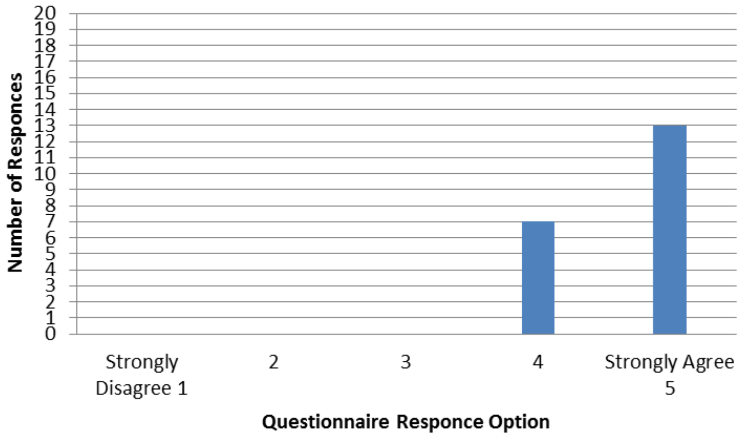
- **Playing game with keyboard and mouse is more fun than using origami. ***



- **I would like to use computer with origami more and more in the future. ***

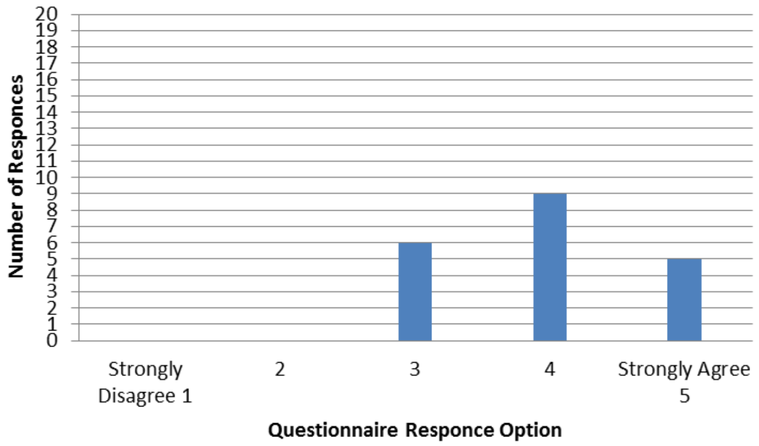


- **I would recommend it to my friends. ***



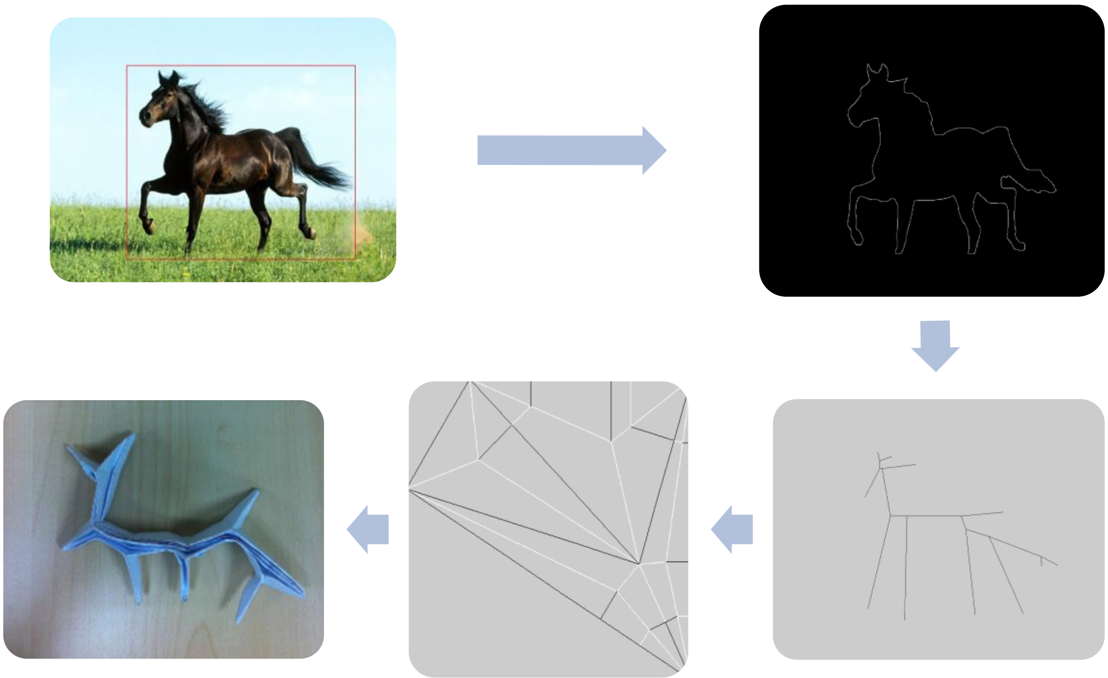
- Cost of Origami Tower

- **I am willing to pay for it. ***

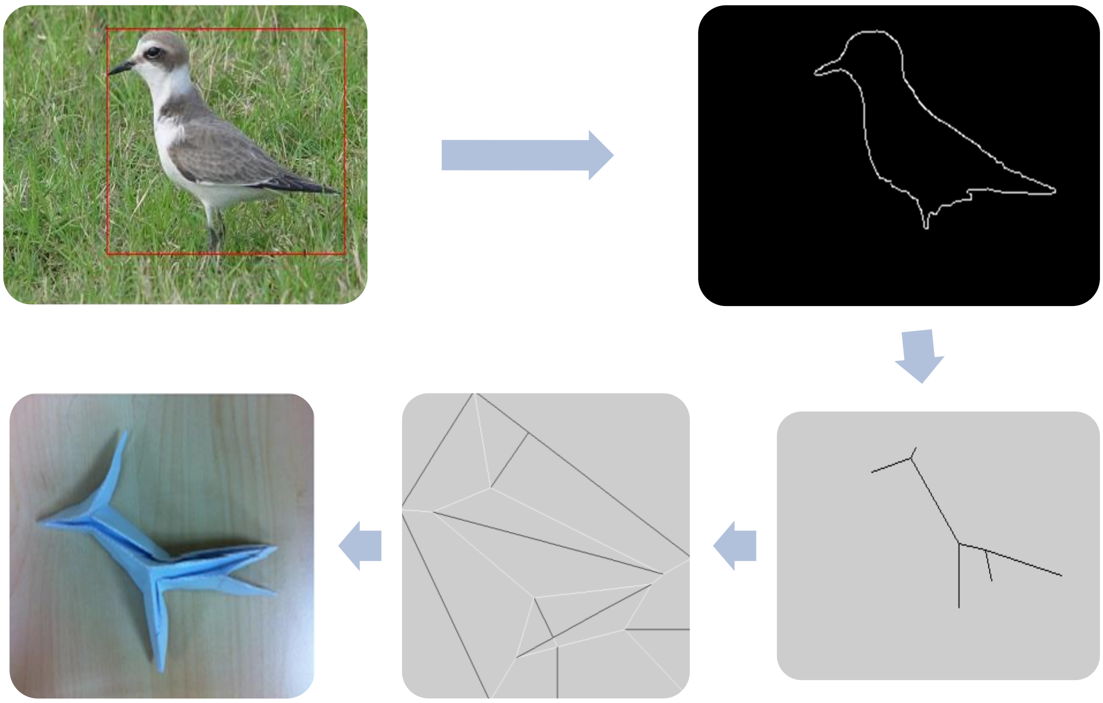


Appendix D: Details of the Examples using Snap-n-Fold

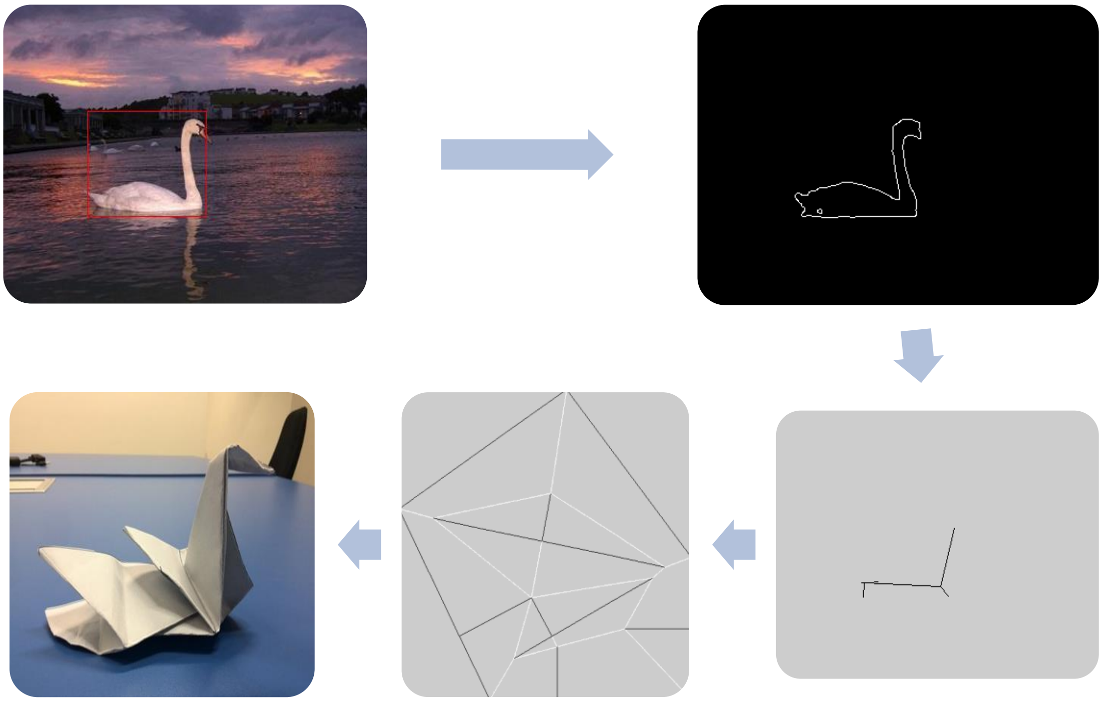
1. Horse



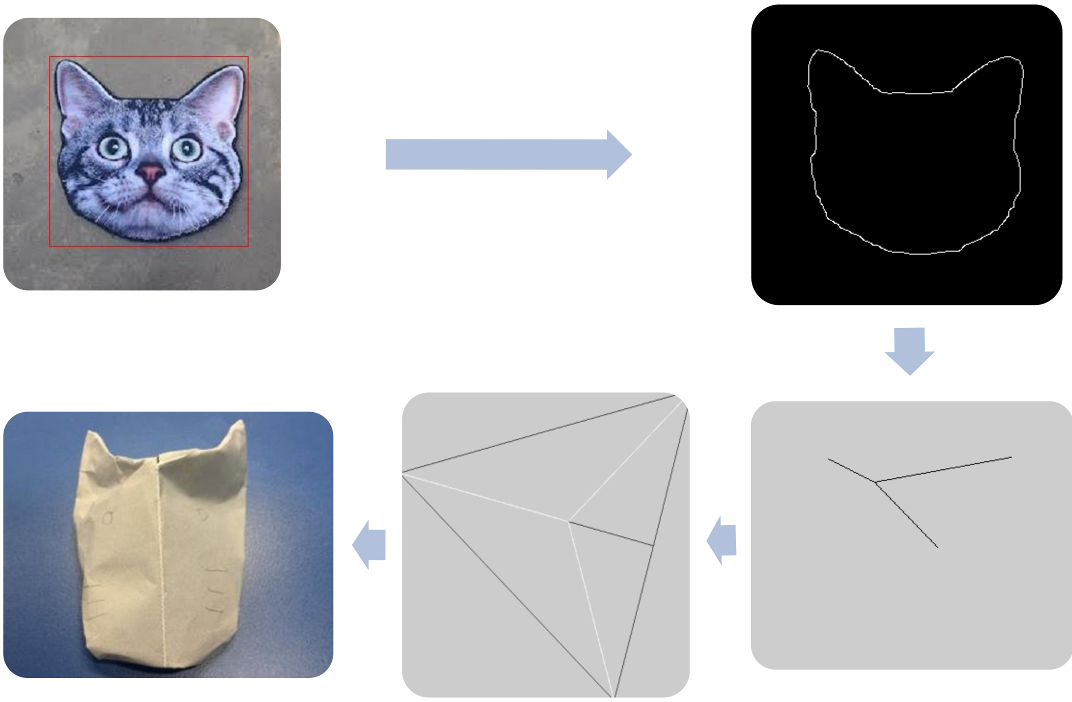
2. Bird



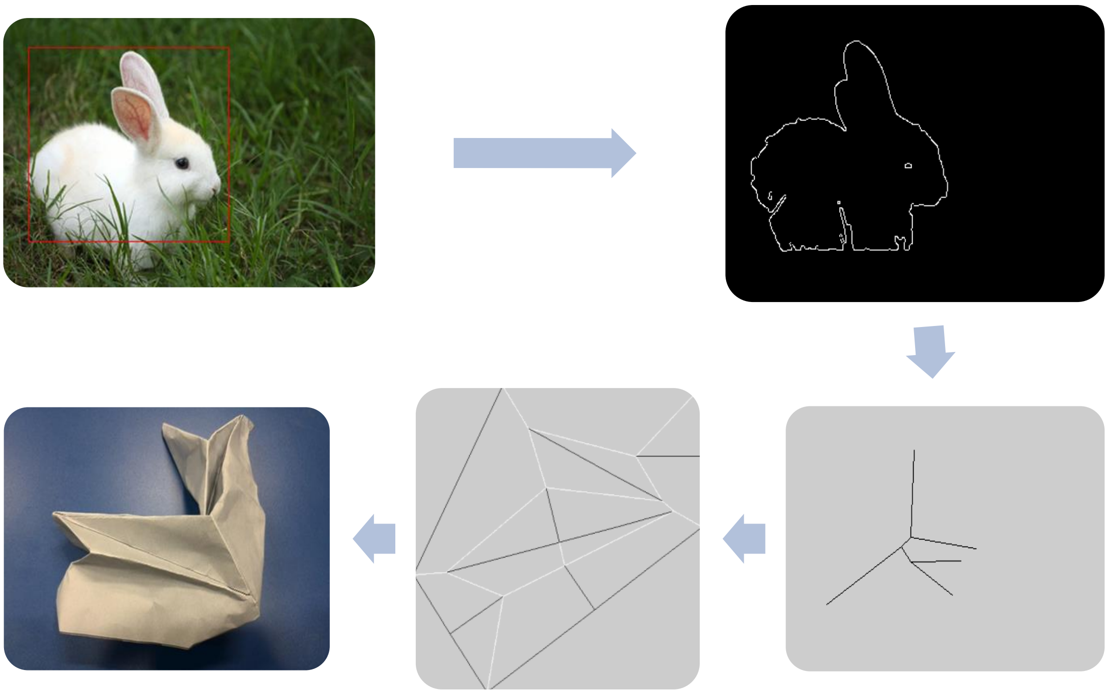
3. Swan



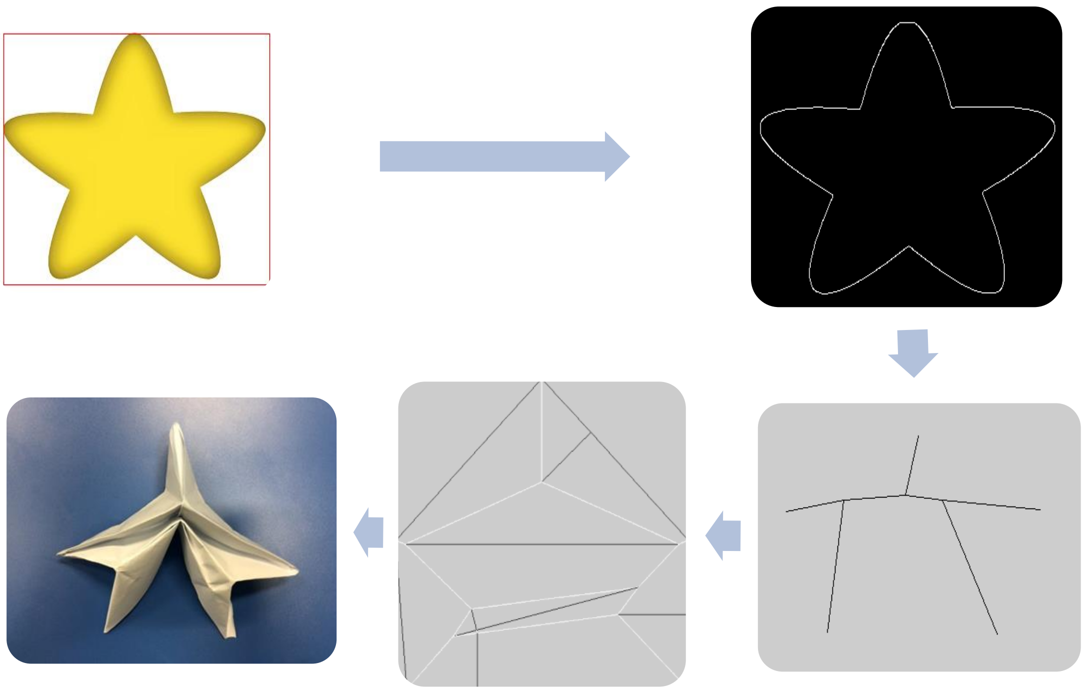
4. Cat



5. Rabbit



6. Star



Appendix E: Questionnaire on Snap-n-Fold

User study on Snap-n-Fold

Thank you very much for participating in this study. I hope you enjoyed using Snap-n-Fold. Here are some questions about your experience in this activity. Your answers would help us understand and improve our research better.

* Required

Gender * _______

Age * ______

Prerequisite Skill: Paper-craft

***What is your previous experience of creating paper-craft, such as origami, paper pop-up?**

Never try □ Beginner □ Intermediate □ Expert □

- Ease of Learning: How do you think of learning to use Snap-n-Fold?

The tutorial is clear for me to learn how to use Snap-n-Fold. *

Strongly Disagree 1 2 3 4 5 Strongly Agree

It is easy for me to learn to use Snap-n-Fold. *

Strongly Disagree 1 2 3 4 5 Strongly Agree

- Ease of Use: How do you think of using Snap-n-Fold?

It is easy to load a picture and select what I want to fold. *

Strongly Disagree 1 2 3 4 5 Strongly Agree

It is easy to fold the origami generated by Snap-n-Fold. *

Strongly Disagree 1 2 3 4 5 Strongly Agree

- Usefulness: How do you think of the functionality of this technology?

With Snap-n-Fold, I can fold an object that I am interested in. *

Strongly Disagree 1 2 3 4 5 Strongly Agree

- Satisfaction: How is your experience of Snap-n-Fold?

It is fun to use Snap-n-Fold. *

Strongly Disagree 1 2 3 4 5 Strongly Agree

I would like to use it more and more in the future. *

Strongly Disagree 1 2 3 4 5 Strongly Agree

I would recommend it to my friends. *

Strongly Disagree 1 2 3 4 5 Strongly Agree

- Cost of Snap-n-Fold

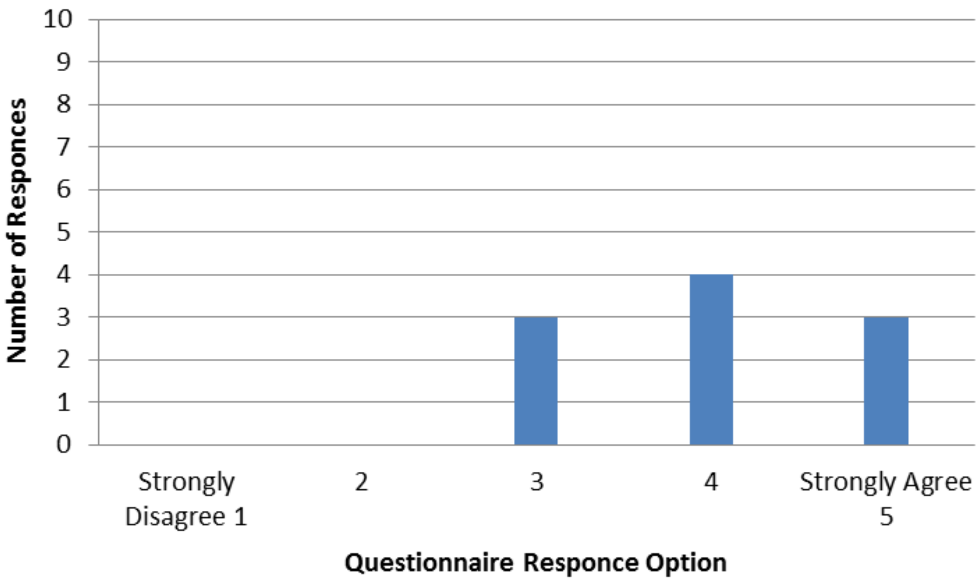
I am willing to pay for it. *

Strongly Disagree 1 2 3 4 5 Strongly Agree

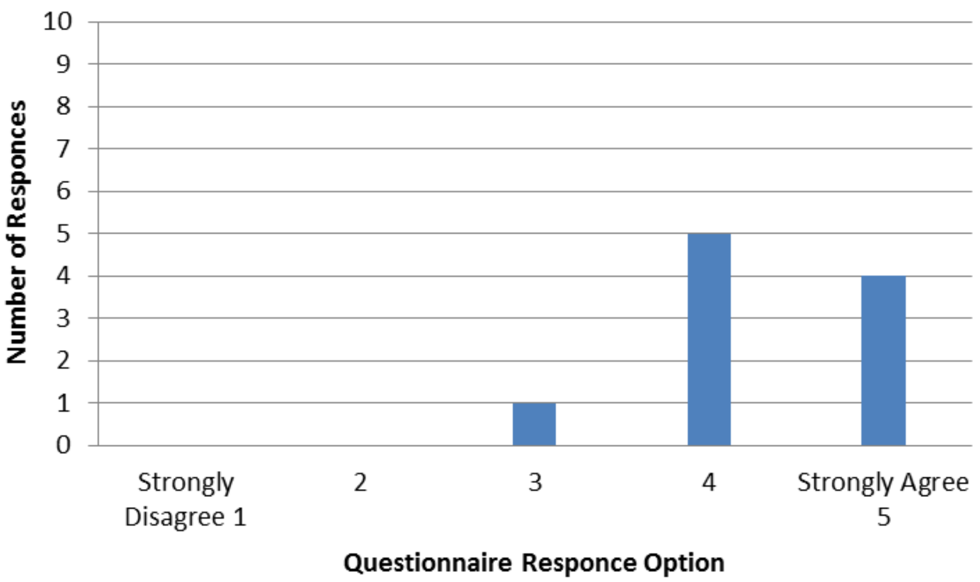
Appendix F: Detailed Distribution of the Results of Questionnaire for Snap-n-Fold

- Ease of Learning: How do you think of learning to use Snap-n-Fold?

The tutorial is clear for me to learn how to use Snap-n-Fold. *

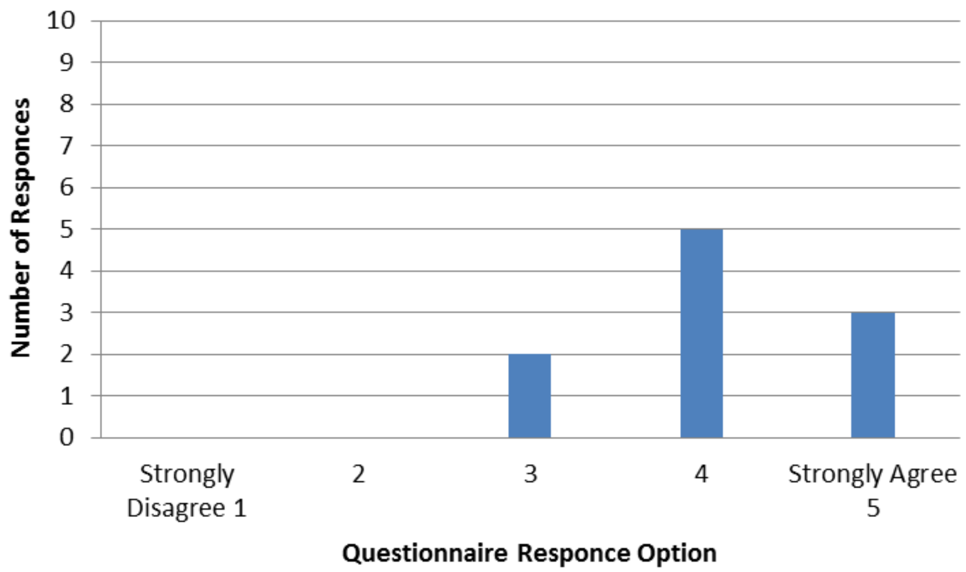


It is easy for me to learn to use Snap-n-Fold. *

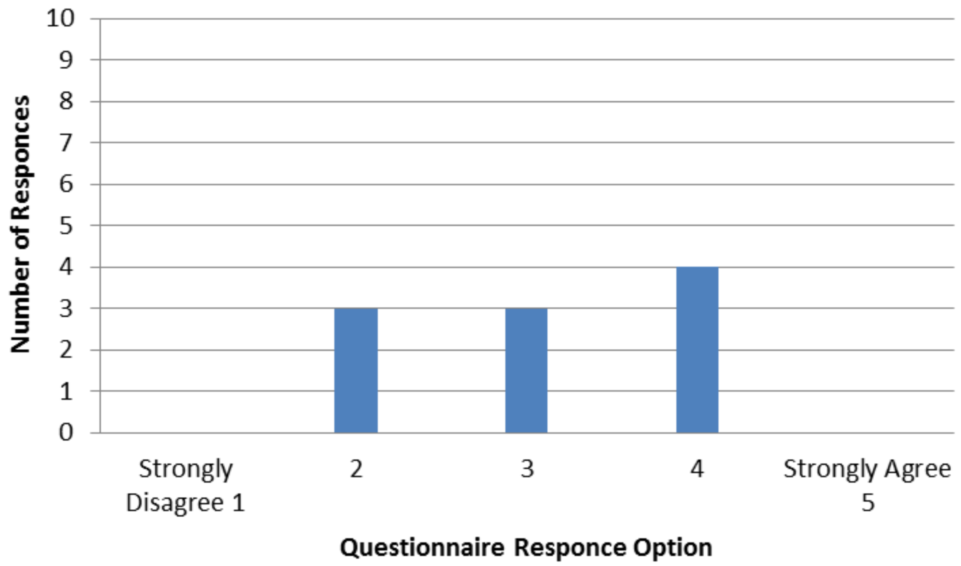


- Ease of Use: How do you think of using Snap-n-Fold?

It is easy to load a picture and select what I want to fold. *

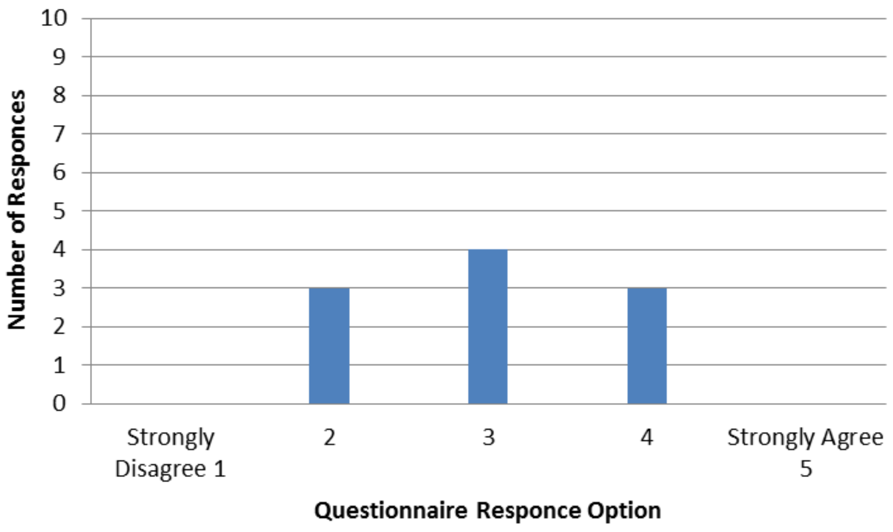


It is easy to fold the origami generated by Snap-n-Fold. *



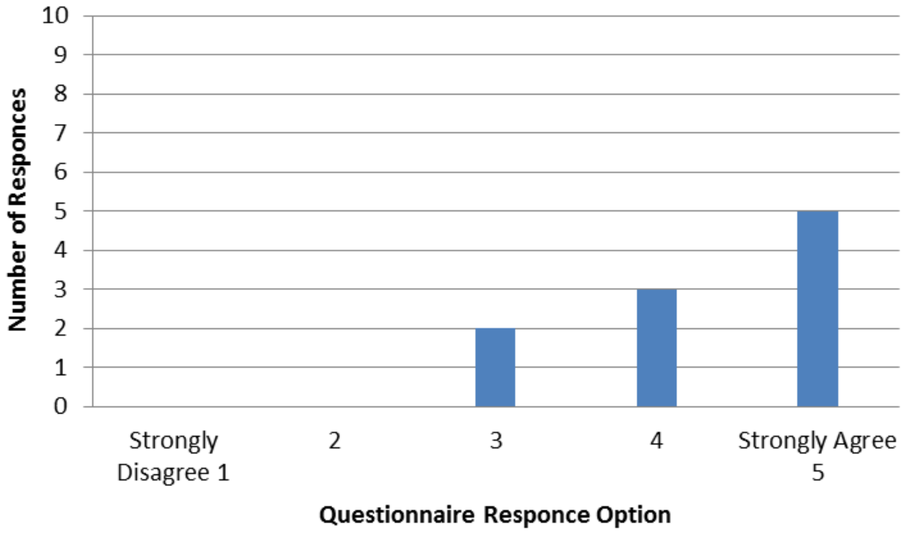
- Usefulness: How do you think of the functionality of this technology?

With Snap-n-Fold, I can fold an object that I am interested in. *

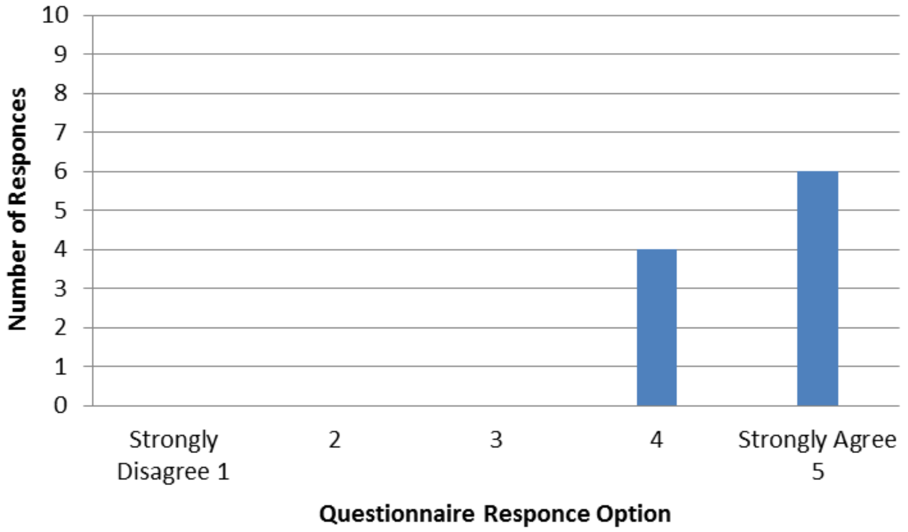


- Satisfaction: How is your experience of Snap-n-Fold?

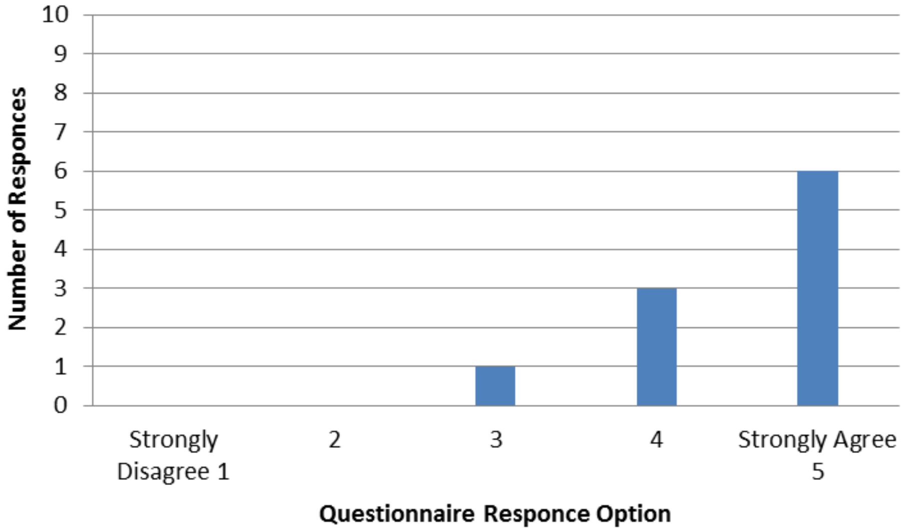
It is fun to use Snap-n-Fold. *



I would like to use it more and more in the future. *

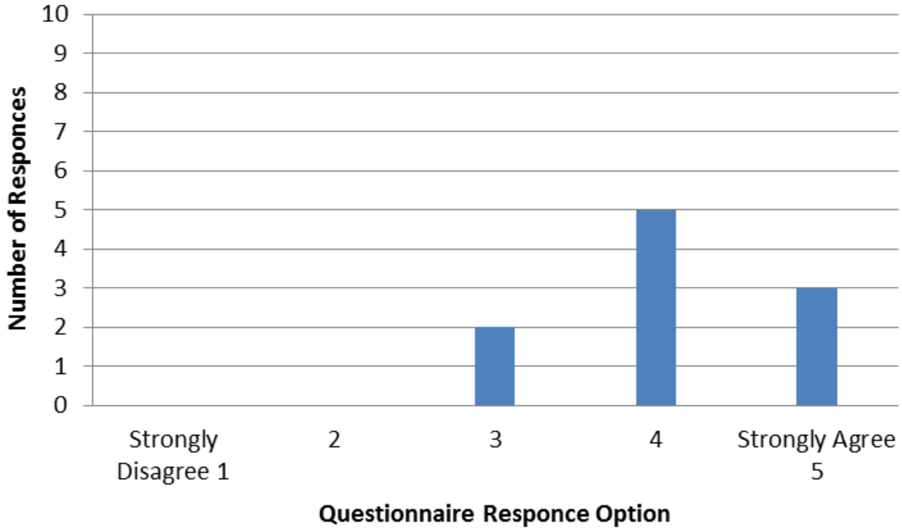


I would recommend it to my friends. *



- Cost of Snap-n-Fold

I am willing to pay for it. *



Appendix G: Questionnaires on Workshop Experience and Usage of the Toolkit

Name:

Gender:

Age:

Skill of paper craft: Beginner Intermediate Experienced

Skill of electronics/engineering: Beginner Intermediate Experienced

Thank you very much for participating in this workshop. I hope you enjoyed making automatic movable paper-craft with wireless power technology. Here are some questions about your experience in this activities. Your answers would help us understand and improve our research better.

- Ease of Learning: How do you think of learning to use this toolkit?

- **The tutorial is clear for me to learn how to use this toolkit to create automatic movable paper craft.**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

- **It is easy for me to learn to use this toolkit.**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

- Ease of Use: How do you think of using this toolkit?

- **It is easy to use this toolkit to create automatic movable paper craft.**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

- **It is easy to use the software to design and plan the movements of the paper craft**
  Strongly Disagree 1 2 3 4 5 Strongly Agree

- **It is easy to integrate the wire to paper craft.**
  Strongly Disagree 1 2 3 4 5 Strongly Agree

- **This toolkit allows me to explore different possibilities of automatic movable paper craft.**

Strongly Disagree 1 2 3 4 5 Strongly Agree

- **I can recover from wrong design easily with this toolkit.**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

- **I can create automatic movable paper craft quickly using this toolkit.**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

- Usefulness: How do you think of the functionality of this toolkit?

- **The software is useful to design and plan the movements of the paper craft**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

- **This toolkit is useful in creating automatic movable paper craft.**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

- Engagement: How is your experience of using this toolkit?

- **Making automatic movable paper craft with this toolkit is fun.**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

- **I enjoy working by myself on creating automatic movable paper craft using this toolkit.**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

- **I enjoy working with group mates on creating automatic movable paper craft using this toolkit.**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

- Satisfaction: How do you like this toolkit?

- **I became creative in automatic movable paper craft with this toolkit.**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

- **I felt this toolkit limits my creativity**

Strongly Disagree 1 2 3 4 5 Strongly Agree

- **I became productive in automatic movable paper craft with this toolkit.**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

- **I don't feel productive with this toolkit**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

- **I would like to use this toolkit more and more in the future.**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

- **I would recommend it to my friends.**

  Strongly Disagree 1 2 3 4 5 Strongly Agree

Any other comments on how we can improve this toolkit? Anything you don't like?

Thank you very much for your participation!

Appendix H: Detailed Distribution of the Results of Questionnaire of AutoGami Workshop

Questionnaire Section: Ease of Learning

The tutorial is clear for me to learn how to use this toolkit to create automatic movable paper craft.

Strongly Disagree 1 2 3 4 5 Strongly Agree

It is easy for me to learn to use this toolkit.

Strongly Disagree 1 2 3 4 5 Strongly Agree

Questionnaire Section: Ease of Use

It is easy to use this toolkit to create automatic movable paper craft.

Strongly Disagree 1 2 3 4 5 Strongly Agree

It is easy to use the software to design and plan the movements of the paper craft.

Strongly Disagree 1 2 3 4 5 Strongly Agree

It is easy to integrate the wire to paper craft.

Strongly Disagree 1 2 3 4 5 Strongly Agree

This toolkit allows me to explore different possibilities of automatic movable paper craft.

Strongly Disagree 1 2 3 4 5 Strongly Agree

I can recover from wrong design easily with this toolkit.

Strongly Disagree 1 2 3 4 5 Strongly Agree

I can create automatic movable paper craft quickly using this toolkit.

Strongly Disagree 1 2 3 4 5 Strongly Agree

The software is useful to design and plan the movements of the paper craft

This toolkit is useful in creating automatic movable paper craft.

Questionnaire Section: Engagement

Making automatic movable paper craft with this toolkit is fun.

Strongly Disagree 1 2 3 4 5 Strongly Agree

I enjoy working by myself on creating automatic movable paper craft using this toolkit.

Strongly Disagree 1 2 3 4 5 Strongly Agree

I enjoy working with group mates on creating automatic movable paper craft using this toolkit.

Strongly Disagree 1 2 3 4 5 Strongly Agree

Questionnaire Section: Sactisfaction

I became creative in automatic movable paper craft with this toolkit.

Strongly Disagree 1 2 3 4 5 Strongly Agree

I felt this toolkit limits my creativity.

Strongly Disagree 1 2 3 4 5 Strongly Agree

I became productive in automatic movable paper craft with this toolkit.

Strongly Disagree 1 2 3 4 5 Strongly Agree

I don't feel productive with this toolkit.

Strongly Disagree 1 2 3 4 5 Strongly Agree

I would like to use this toolkit more and more in the future.

Strongly Disagree 1 2 3 4 5 Strongly Agree

I would recommend it to my friends.

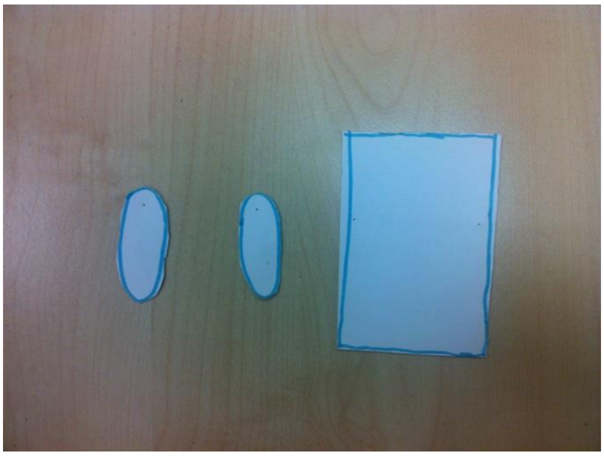
Strongly Disagree 1 2 3 4 5 Strongly Agree

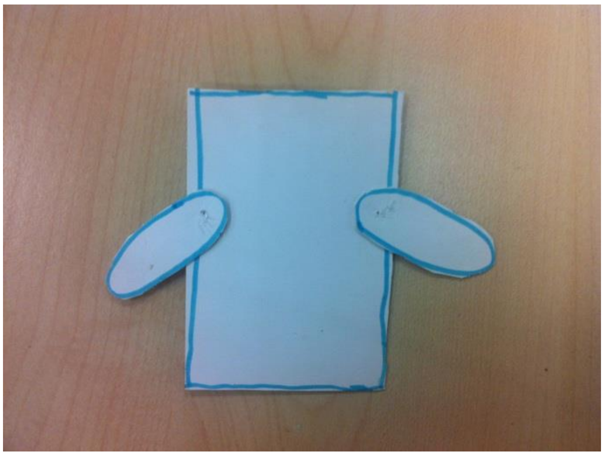
Appendix I: Step-by-Step on using Autogami Software and Hardware to create Automated Movable Paper Craft

- The First Example

1. As the first step, you can create the physical parts of your movable paper craft. Here, as a simple example, I create one big rectangle, and two circles.

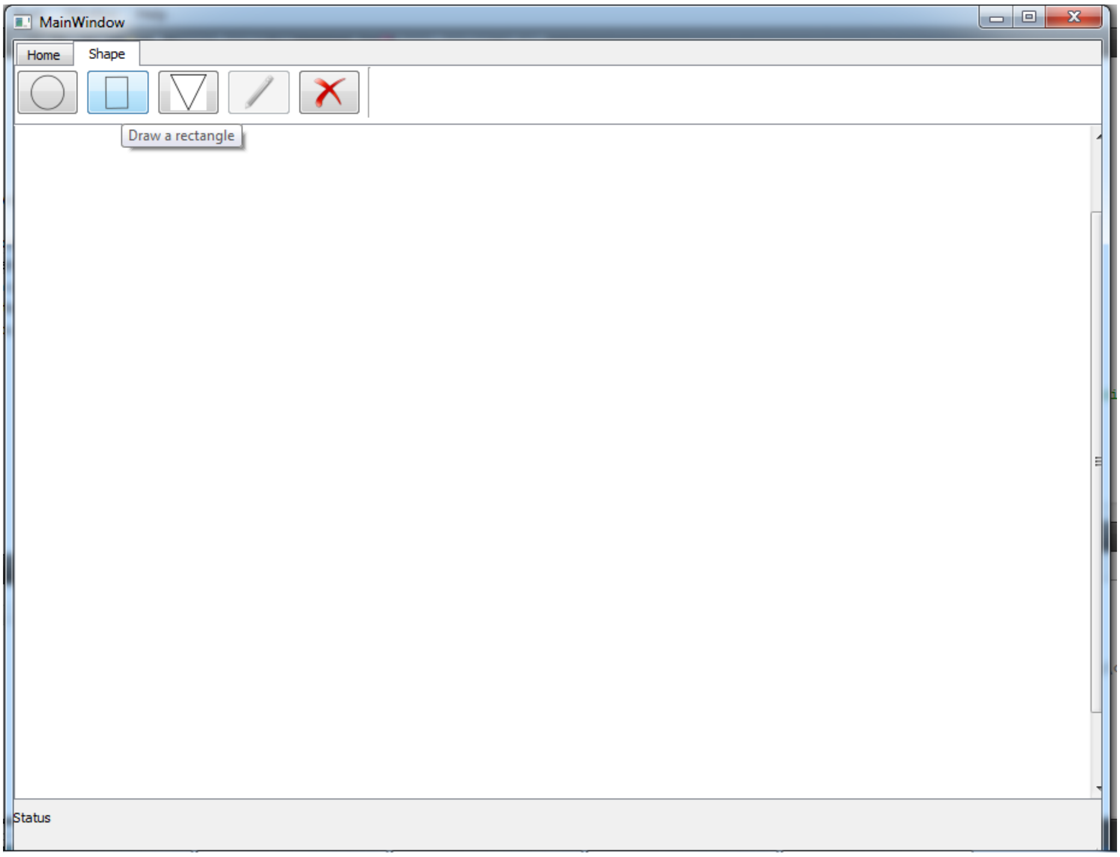
2. Then you can attach the parts together, as the normal paper craft, using wire and needle.

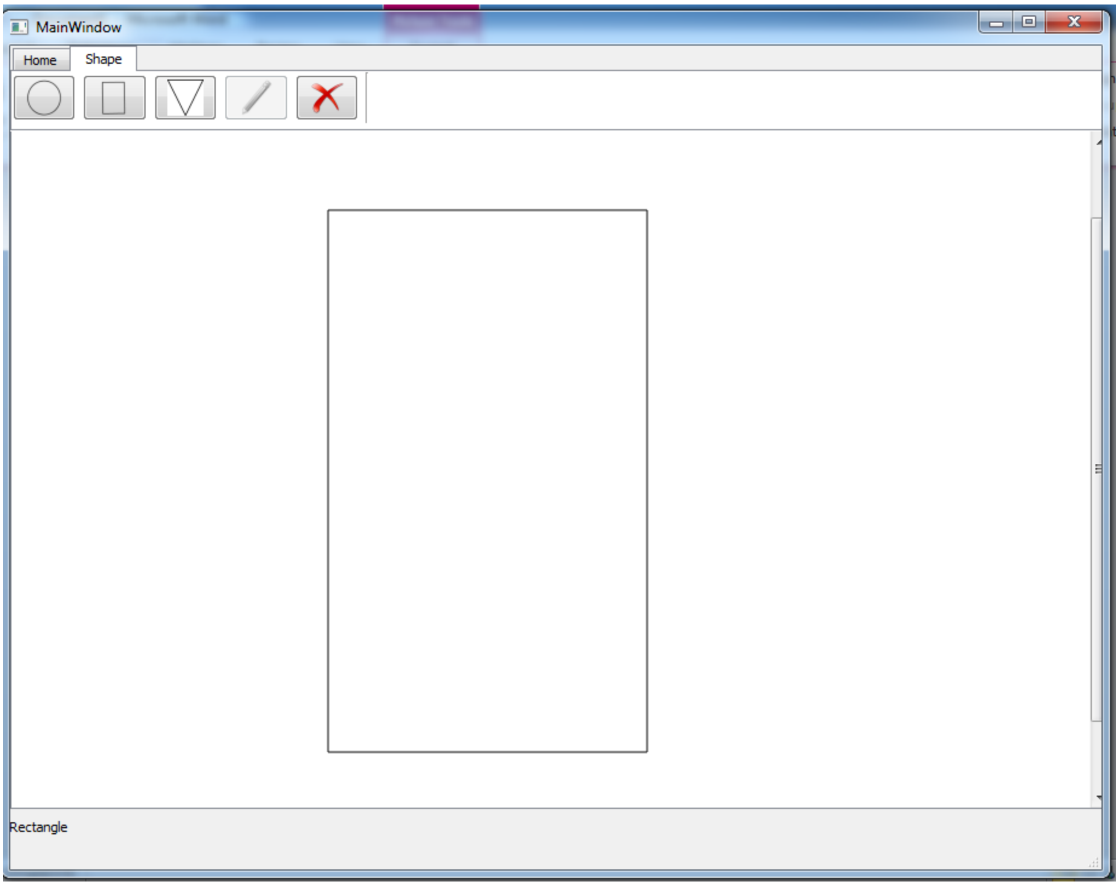




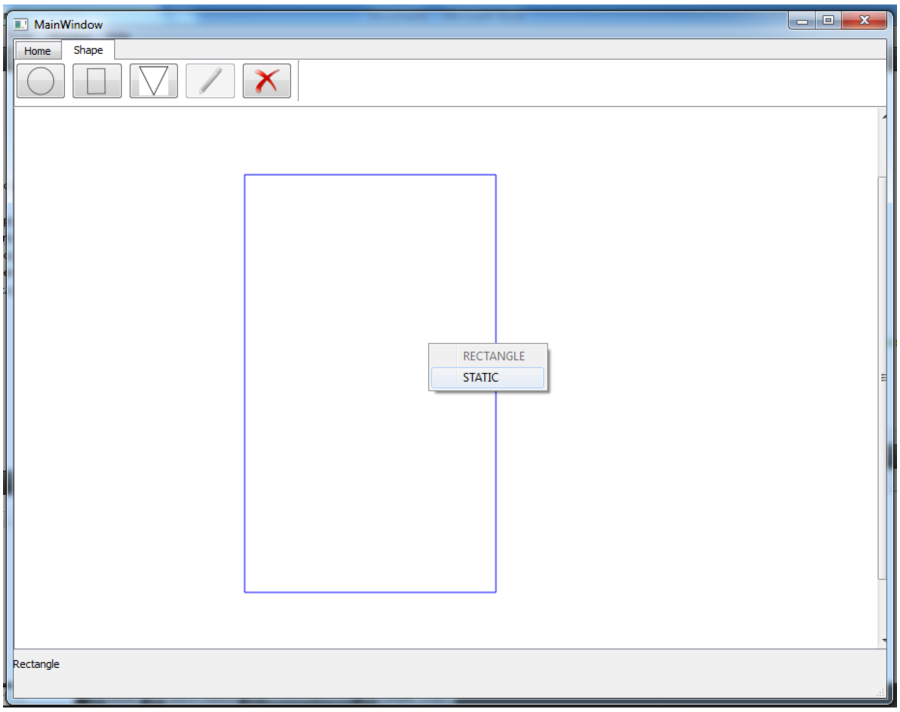
3. After finishing the normal paper craft, we can come to the AutoGami software to plan the automated movements of the paper craft. First, we draw a similar shape of the physical paper craft that we just created. In page "*Shape*" of the AutoGami software interface, you can see three shape buttons: circle, rectangle, and triangle. You can draw these shapes on the canvas by selecting related buttons. As the example, I click on Rectangle button, and

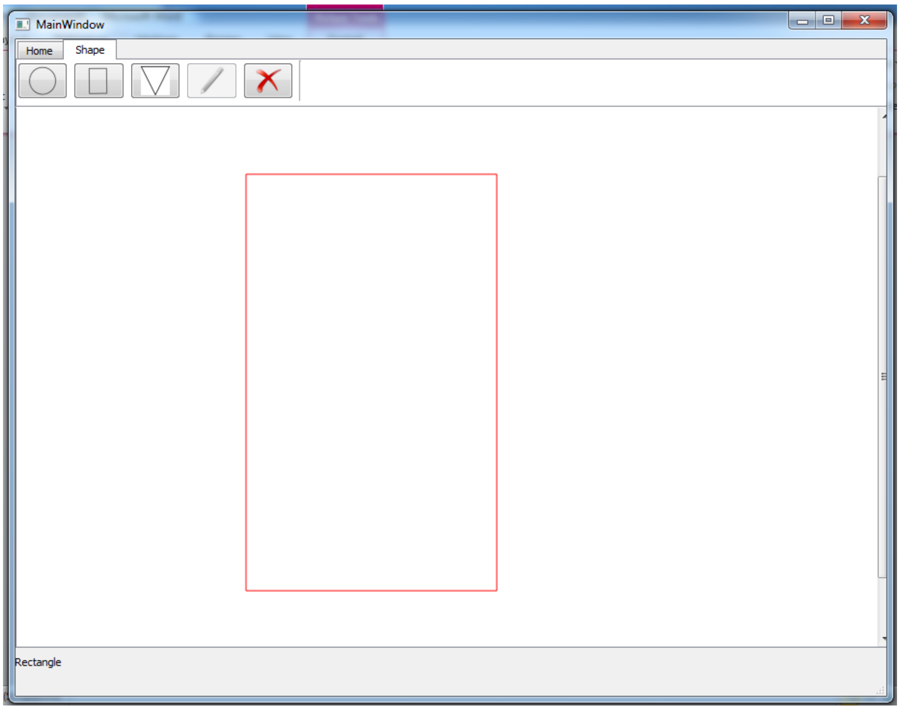
then draw a rectangle on the canvas.



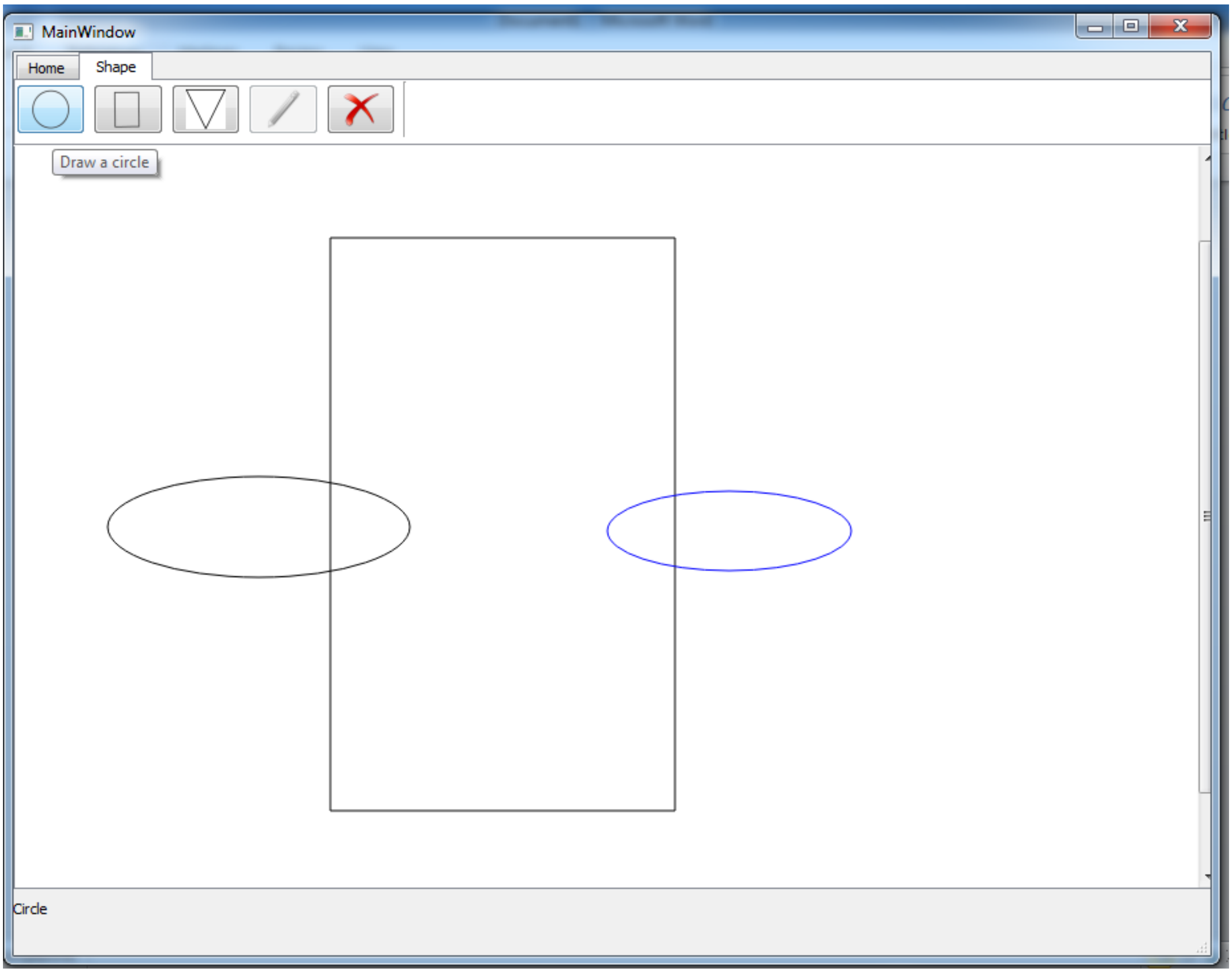


4. After drawing the rectangle, we have to identify it as a static part, because it doesn't move in the automated paper craft. By right-clicking on the rectangle, we can check the "STATIC" option, to achieve this goal. After being checked as the Static part, the rectangle becomes red when being clicked on.

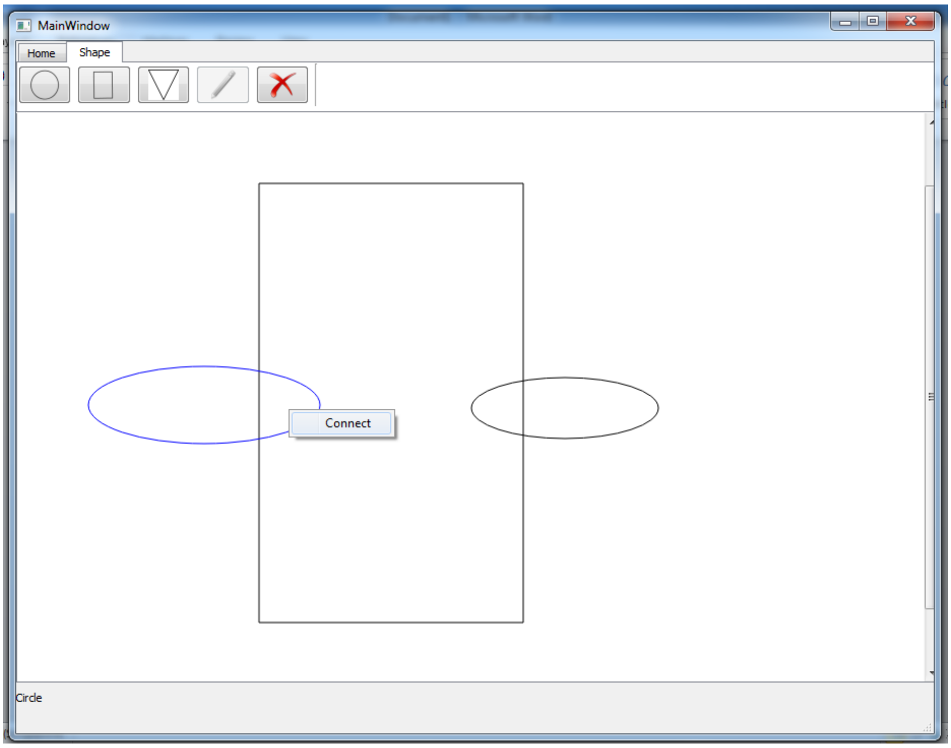


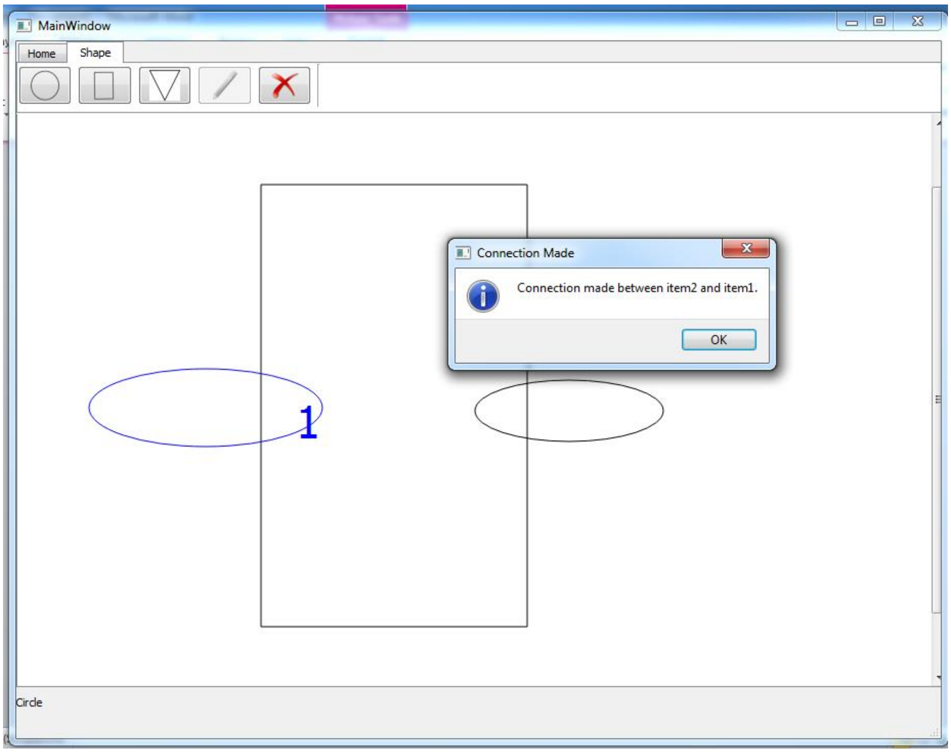


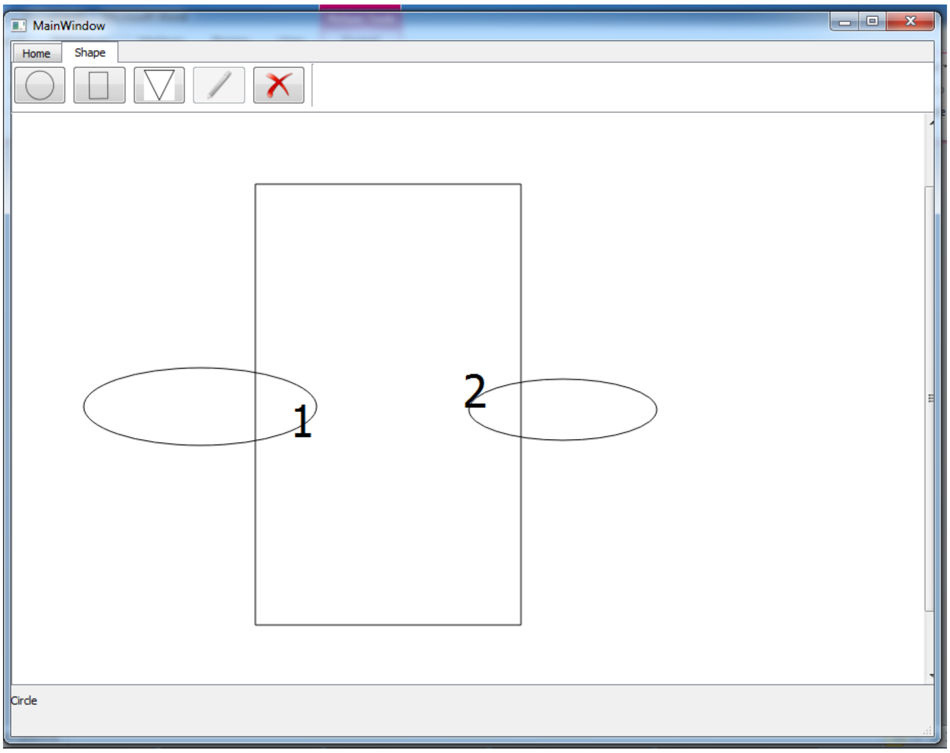
5. Similarly, we can draw the other parts: two circles, by clicking the Circle button. But we may not need to identify them as Static, since we want them to move automatically.



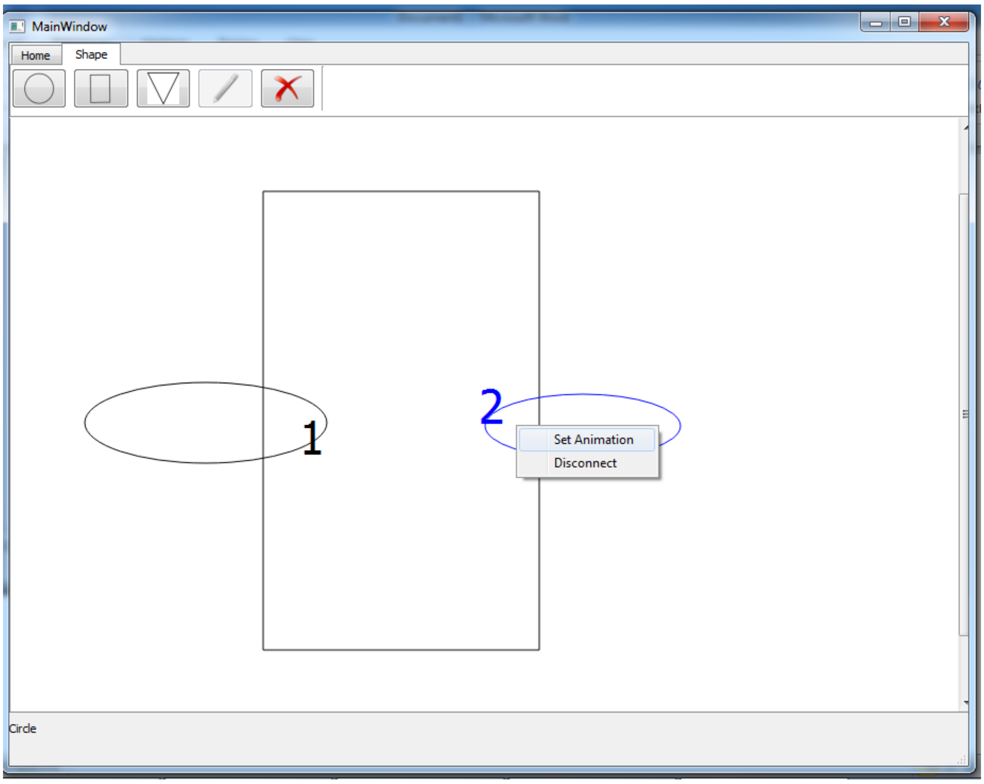
6. After finishing the parts, we can start to connect the parts. By clicking the intersection part of two parts, we can see a pop-up menu with “Connect” button. By clicking the “Connect” button, two parts will be connected. And the connection ID will be displayed near the connection port.

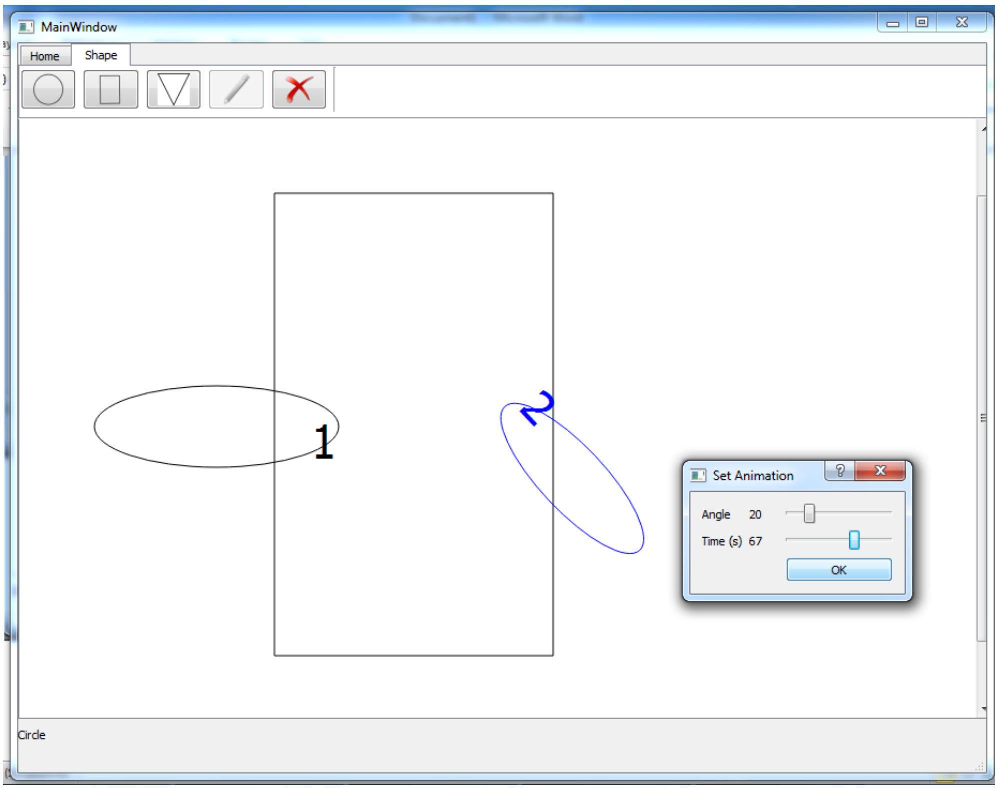






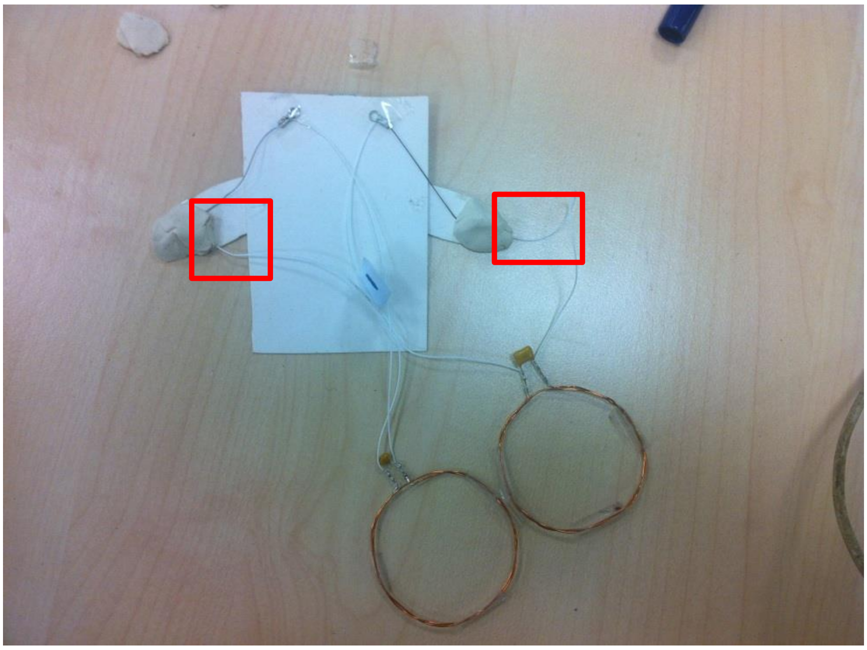
7. After connecting the parts accordingly, we can start to animate our drawing. Again right-click on the intersection parts, a new menu will pop up this time. Here we can select to set the animation in the pop up dialog, by selecting the angle and the duration time of each part.



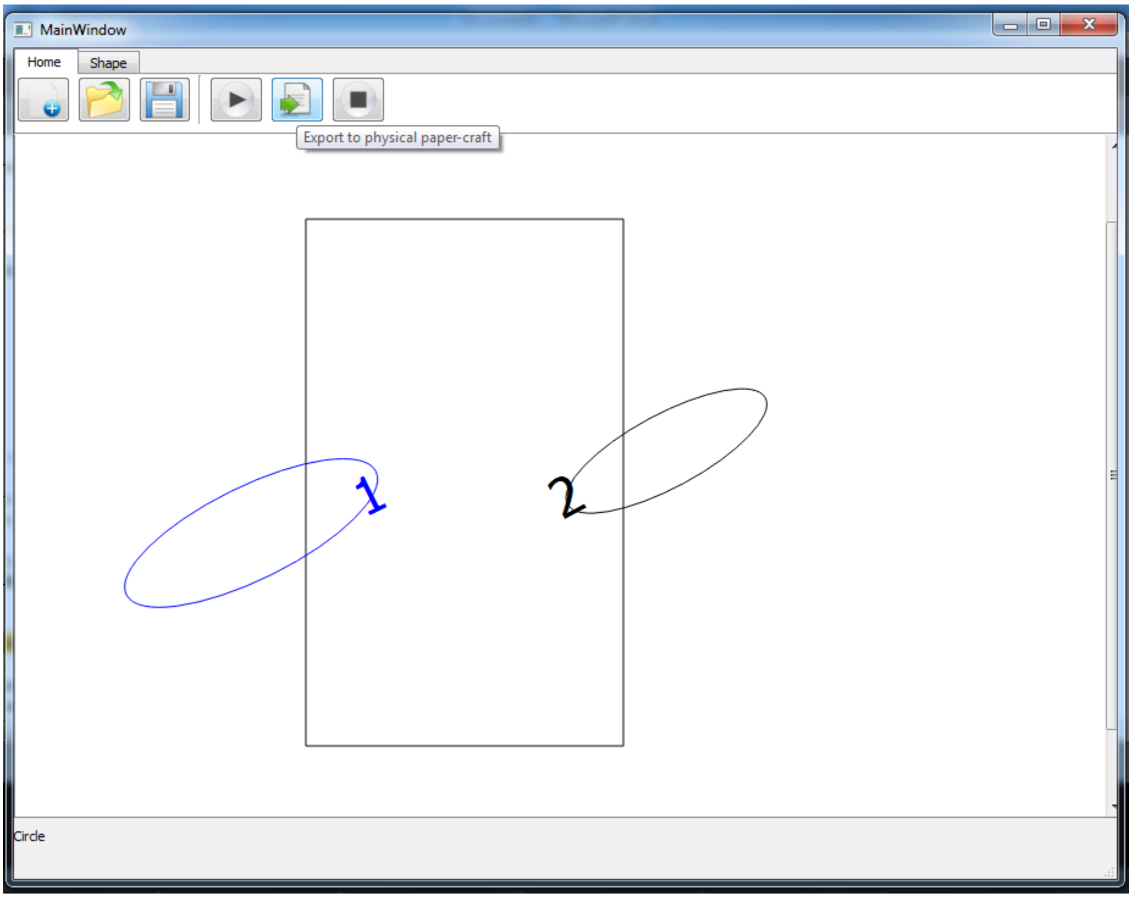


8. Then we can come back to the real world. We have two power receiving coils with Shape-memory Alloys and IDs: 1 and 2. These IDs are mapped to the connection IDs in the software drawing. Therefore, we can attach these SMAs to different parts of the physical paper-craft, according to the IDs.

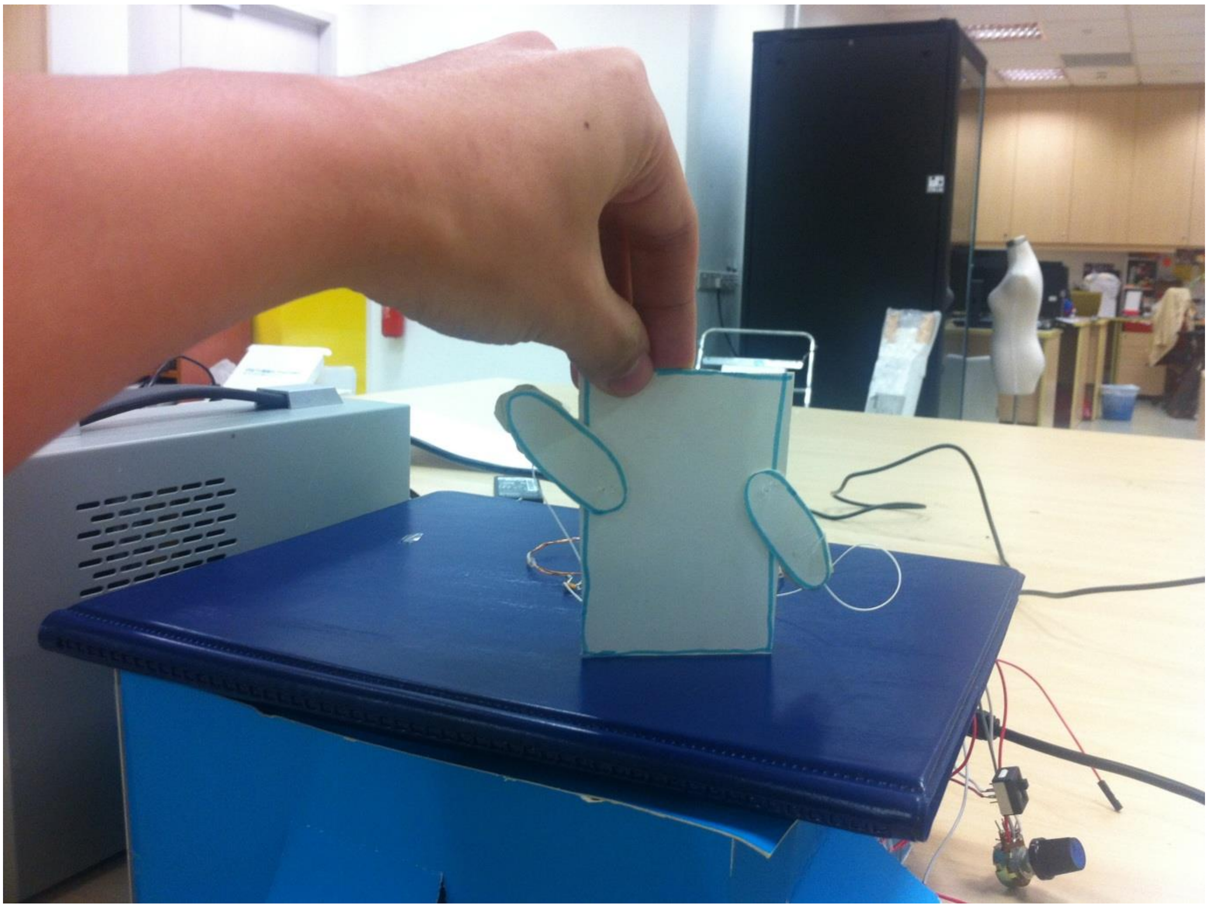
9. We can also attach some extra clay to the moving part, to make it easy to reverse back when the shape-memory alloy is not activated.



10. After attaching the SMAs, we can go back to software. In the “Home” page, we can click the “Export to physical paper” button to activate the hardware: wireless power surface.



11. Now when we put the physical paper craft on the power surface, it can move automatically.



- Summary

1. Make the physical movable paper craft.

2. Draw the similar shapes and structure in the AutoGami software interface.

3. Identify the static part which doesn't move in the physical paper craft.

4. Connect the movable parts to the static part.

5. Set the animation of each connection.

6. Come back to the physical world! Attach shape-memory alloys to the parts of the real paper craft, according to the ID displayed in the Autogami software.

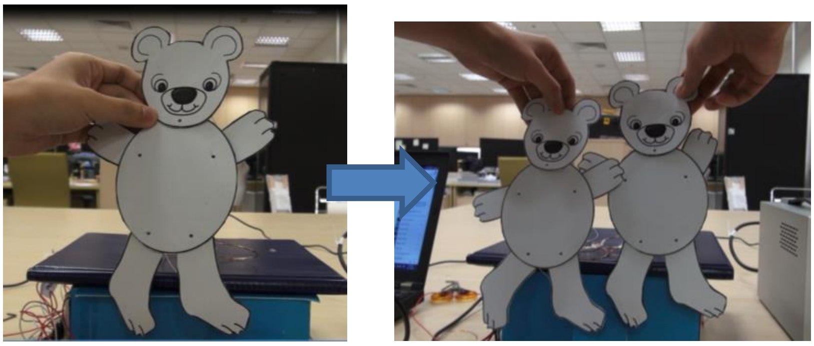
7. Click the "Export" button in the Autogami software.

8. Place the automated paper craft on the power surface, and enjoy the animation~

- Some More Examples You Can Make Using AutoGami

- The feature of physical copy & paste in Autogami

After you create an automated movable paper craft, you can copy the movements to another paper craft which has the same physical structure, by attaching the same power receiving coils and SMAs to the same position of the other paper craft.



- More Fun

Here are some more interesting examples of automated paper craft that you can make with AutoGami.