PCB Origami

Folding circuit boards into electronic products

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Submitted to the
Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements of the degree of
Master of Science
at the Massachusetts Institute of Technology

May 2013
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Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning, on May 15th, 2013, in partial fulfillment of the requirements for the degree of Master of Science in Media Arts and Sciences

Abstract

PCB origami is a concept for an alternative manufacturing process of electronic products, in which the electronic material will be manufactured flat and folded into functional 3D graspable products by the user. PCBs will be used both as the functional electronic material and the structural material of the products. This thesis work explores the fabrication, design and interaction aspects of this concept, by demonstrating a series of case studies. The fabrication aspect was examined by creating a straightforward customization workflow of electronic products, and by developing a series of prototyping techniques for PCB lamination. The design aspect was researched through the creation of a new type of electronic products that can be completely flat when not in use, and can be folded once needed. The user interaction aspect of the PCB origami concept was studied in the contexts of foldable surfaces with embedded information on how to fold them and by demonstrating a foldable PCB product that is able to change its shape based on the desired task.

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Acknowledgements

This thesis work concludes my journey of two years at the Media Lab. It was an incredible journey, full of insights and inspiration but also challenges and difficulties. I would like to express my deepest gratitude to the wonderful people that I have met during my way and helped me get to where I am now. I especially would like to thank the following:

My advisor, Neri Oxman. Thank you for believing in me and supporting me. I will never forget your kindness, positive approach and enthusiasm. Thanks you for showing me the beauty of the structures in nature and for opening my mind to so many ideas, research works and concepts. Thank you for letting me find my own path, even after going into some dead ends.

My readers, Pattie Meas and Henry Holzman. Thank you for pushing me, challenging me and inspiring me during our meetings this past year. Thanks for all your advice and feedback, your contribution to this thesis is significant.

My research group, Ben Peters, Steven Keating, Liz Tsai, Michal Firstenberg, Markus Kayser, Jared Lucas, Carlos David González, Federico Mazzolini and Zjenja Doubrovski. Thank you for your advice, your support and for your friendship. I am delighted to have met all of you.

A special thanks for Roy Shilkrot. Thanks for helping me with the customization software. I really appreciate your friendly help, and enjoyed discussing my project with you.

My loyal UROP Henry Skupniewicz, thank you for your assistance during the last three semesters. It was a pleasure working with you.

My wonderful and loving parents, Alex and Paula Sterman. Thank you so much for your support from a distance. Your absolute faith and unconditional support in my decisions, are giving me the confidence and self-assurance for moving forward.
And lastly and most importantly, I would like to thank my wonderful wife Dana. Thank you for enormous effort in supporting me, while taking care of our two kids and working full time. Thank you for letting me pursuit my goals and dreams. Thank you for listening, cheering, and encouraging me in difficult times. You are the source of my strength and happiness. This thesis is dedicated to you with love.
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1. Introduction

1.1 Man-made objects vs. natural structures

A fundamental difference exists in the relation between multiple functionalities and structure in man-made artifacts and in biological structure. In nature, variation in properties or functions is achieved by changes in the structure (or micro-structure) and in the composition of materials, whereas in manufacturing, changes in properties are typically achieved by assembly of materials with different properties [1]. Those materials are traditionally classified as structural materials or functional materials. Structural materials are used for their mechanical properties (such as strength) and functional materials are being used for exploiting a specific characteristic, such as thermal or electrical conductivity [2]. In nature, on the other hand, structural materials such as bones or wood perform also as functional materials, in the way they are pumping water up to the leaves or storing energy.

Over the years of evolution, nature had developed sophisticated composites that are multifunctional and structural, can vary properties along the material system and adapt to changes. Those composites are examples of nature ability to use limited resources for achieving optimal properties. For example, the cell walls of all plants are composed from micro-structural compositions of only four materials building blocks: cellulose, hemicellulose, lignin and pectin. Different rations and structural arrangement of those building blocks result materials with wide range of strengths, from stems of palm trees with Young’s module of 30GPa to liquid-filled foam-like parenchyma cells of apples and potatoes with Young’s module of only 0.3MPa [3]. A different example of functional integration can be found in a typical leaf. The vines of leaves are both functional and structural materials. The vines act as channels that provide nutrients to the leaf’s cells but also perform as a flexible spine that helps the leaf carry the weight of water drops without breaking.
Manufacturing, on the other hand, is characterized by functional separation. When multiple functionalities are needed, different materials are assembled, each to support one of those functions. A hammer for example, is composed of a heavy metal piece, a handle from light but strong material (such as wood) and elastomer for gripping and for soft interface with the hand. Each of those materials has a single function when using the product and is made from different material. Those materials need to be processed individually and then assembled. This process usually difficult to automate and thus requires labor. In addition, areas of connection of the different materials have a high potential of failure. An additional example can be found in electronic products. Generally, electronic products are manufactured by assembly of a Printed Circuit Board (PCB) and plastic enclosures. The PCB is the electronically functional material of the product and enclosures are the structural materials, giving the products its physical form, structure and appearance.

1.2 VPN – Variable property Design

Digital fabrication technologies allow designers to gap the differences between traditional manufacturing methods and the way natural structures are designed [4]. Variable Property Design approach (VPN) was developed by N.Oxman [1] as a set of processes for distribution of materials and property in a design of a product. The concept of VPN is to design and fabricate materials while organizing their structure in a way their properties vary in correspondence to functional constraint and needs. Fabrication of materials with variable properties and functional integration can be achieved by using 3D printing technology with digital materials as enabled on the Stratasys’s Connex 3D printers [5]. Those 3D printers have a two inkjet printer heads that can deposit two different materials. In the design process, it is possible to decide which material will be deposited in each voxel (3D pixel) inside of the volume of the printed structure. This allows designing not only the form of an object but also its material structure. Furthermore, given the small resolution of the printer, the printed droplets are in the diameter of 50 microns, the Connex 3D printers allows creation blends of the two printed materials. If a flexible material is used in one printer head
and a rigid one in the other, the printer can produce a range of semi-rigid materials depending of the ratio of the mix. This principle is used in the Beast a chaise lounge chair by N.Oxman[1]. The chair is composed of a continuous surface with a pattern of integrated tiles that vary in stiffness. The surface itself varies in thickness and pattern density in order to support the load and on the same time provide comport (Figure 1).

Figure 1 – “Beast” 3D Prototype for a Chaise Lounge by N. Oxman, printed with Stratasys ConneX 3D printer

1.3 PCB as material with variable properties

PCBs are composite materials made by a lamination of conductive an insulative material. Traces are etched from a plates covered with copper and the then glued and stacked in layers with the insulative material in between. In the assembly process of the fabrication of PCBs, Pick-And-Place assembly machines automatically attach components on the surface of the PCB, which are connected to the traces on the PCB and complete its electronic functionality. PCB designers can control the property and location of each component of the circuit, and decide which areas on the PCB will be conductive. In addition, the designers can also decide on the size and on the outline of the PCB. PCB is in fact, a material with variable properties, as designers can digitally control the property of each “pixel” on the surface of the material. They can choose whether it will be conductive, if a specific component be placed and what kind of component. Moreover, depending on the substance that composes the PCB, the
mechanical properties of the material can be determined. Designers of rigid-flex PCBs can actually plan that some specific areas will be rigid and other areas will be flexible.

1.4 Using PCB as structural material

As mentioned above, PCBs are usually being used only as functional materials in electronic products. PCBs are the heart and core of every electronic device, but they are usually hidden inside the enclosure and invisible for the user. In the research presented in this document, I am proposing using PCBs not only as functional materials but also as structural material. The electronic traces and components will be incorporated in the outer shell of the product. Products will no longer need to be assembled; they will be composed only from one part.

As for today, PCBs are manufactured flat, as two dimensional (2D) sheets. In order to turn those sheets into 3D objects I am suggesting using an ancient method- folding. Folding of electronic material from a thin sheet to graspable and functional electronic products will allow creating products that are completely flat and can be folded once needed. In this work I have researched applications and features that are enabled by this approach; sheets that can guide the user on the correct way of folding them, products that can change their form to fit a specific task, and products that can be easily customized to fit the physical dimensions of a user.

1.5 Contribution

The PCB origami concept suggests an alternative manufacturing process, in which the electronic material will be manufactured flat and folded into functional 3D products by the user. The research focuses on three aspects of this concept: fabrication, design and interaction.

Fabrication

A straightforward concept for implementing mass customization of electronic devices based on fit was demonstrated. Dimensions were extracted from a 2D image of a hand,
and then sent to a CAD file that generated a customized version of a computer mouse based on those dimensions.

In addition, several fabrication techniques for creating rigid-flex PCBs were developed by precise lamination of PCBs with other materials. And, conductive connections were developed for electrically and mechanically connection of edges of PCB.

**Design**

Two examples of novel PCB origami products were demonstrated; an iPad cover that can be folded into a game controller and a flat flexible PCB that can be folded into an air mouse with integrated cable that is ripped out of the PCB and connected to a USB port.

**Interaction**

A PCB that can be folded into both a game controller and a mouse was demonstrated as an example of multifunctional products that will be able to change their functionality upon the specific form they are folded into. Also, a PCB with embedded guidance and verification systems was demonstrated. This PCB uses LED as electronic clues for guiding the user on the correct folding sequence and conductive connection to verify it.
2. Background - PCB technology overview

2.1 PCB Classification

PCB can be classified into three types of boards depending on their construction: single-sided, double-sided, and multi-layered. On single-sided boards wiring and components are available only on one side of the insulating substance. These boards are being used for PCBs with limited functionality when manufacturing costs needs to be kept minimal. In case of more complex circuitry, double-sided PCB can be used. The Electrical connections between the circuits on each side are made by drilling holes through the substrate in appropriate locations and plating the inside of the holes with a conducting material. This technology is the basis for most printed circuit boards that are being produced today. The multi-layered board, has a substrate made up of layers of printed circuits separated by layers of insulation. The components on the surface connect through plated holes drilled down to the appropriate circuit layer. Multi-layered board is used in when a complex PCB is needed for example PCBs of cellphones and computers motherboards.

Figure 2 - Typical rigid-flex PCB board

In this research work a special attention is given to one kind of multi-layer board, the Rigid Flex PCB board. The Rigid Flex PCB is a lamination of flexible boards and rigid boards. The flexible parts of the PCB connect rigid boards (see figure 2). Flexible PCBs are usually manufactured from polyester or polyamide materials with thickness of about
0.1mm, and can be one-sided, double-sided or multiple-layered. Rigid Flex PCB technology is used to achieve volumetric efficiency in compact products.

2.2 The History and the future of the printed circuit board

The invention and development of PCB technology is one of the key factors for the incredible technology progress that characterizes the current and previous centuries [6]. Below is an overview of the history of the development of PCB and its relation to technological breakthroughs.

Before the invention of the PCB, point-to-point wiring techniques such as metal strips or rods were used for connecting components that were mounted on wooded surfaces. Later, the metal strips were replaced by wires that were connected to screw terminals. The first printed circuit patent was filed in 1925 by Charles Ducas for a method of using a stencil and conductive inks to create paths directly on an insulated surface. The invention of the modern PCB is associated to Paul Esler, an Austrian inventor, who patented a technology for etching conductive pattern on copper clad insulation material 1943. While working in the United Kingdom on a radio set, Eisler developed a technique for etching paths of a thin layer of cooper foil that was bonded to a non-conductive base made of glass. Eislar also proposed using conductors on both sides of the copper clad materials, and using eyelets for connection of both sides. However, using plated through holes technology, that was patented the U.S. firm Hazeltyne in 1961, was eventually preferred for connection of double sided PCBs and also laid the foundation of multi layer PCB technology that is in use today. In the 1950s, after the transistor was introduced for commercial use, components became smaller and the need for small packaging of electronic devices grew, as products such as radios and television became popular. As a result more companies started using PCB technology and it became popular. In the 1970s, integrated circuit chips were introduced, and these components were quickly incorporated into printed circuit board design and manufacturing techniques. The next revolution in the manufacturing PCBs started at the 80’s when surface mount component technology was introduced, which led to smaller boards for a
given functionality and lower production costs. Improvements in flexible PCBs and rigid-flex PCB technologies in recent years contributed to advancement of electronic devices especially in the medical and military fields and consumer electronics. While the functionality of devices such as cameras, tablets computers and hard drives increased, the weight and size of these devices have decreased dramatically [7,8,9].

In the future, PCB technology is expected to continue to improve in terms of costs, functionality, and reliability [8]. In addition to improvement in performance, technologies for new processes and materials are being researched. One of those technologies is stretchable PCBs. Stretchable PCBs are PCBs can be stretched, compressed, twisted, bent, and deformed into arbitrary shapes. Application of such PCBs include: wearable computing, sensory robotics skins and also bio-integrated electronics that are implanted in the human body [10]. Another future technology is 3D printing PCBs using conductive and insulative silicone. This approach was demonstrated by Periard at el. [11] by using the platform of Fab@Home 3D printer with dual deposition nozzles. The researchers demonstrate a flash light and a toy with 3D circuit that is also partially flexible. Lastly, processes for embedding active and passive components inside the material thickness of the PCB are being developed. This will allow creating PCBs that are even more compact and dense then today’s PCB. There will be no need to solder components on the surface of the PCB like it is being done today [12].

Future advancement in PCB technology will allow creating materials with embedded electronics with higher degree of material manipulation. PCB could not only be folded but also squeezed, starches and compressed. The components of the PCB will be embedded in the materials itself, and PCBs will be easier to digitally fabricated using 3D printing technologies.
3. Motivation

3.1 Digital fabrication with functional integration

A well known inspiration for researchers of digital fabrication technologies is the imaginary replicator machine from the television series “Star-Trek”- a machine that can produce any complex product or object with multiple materials, in one press of a button [13,14]. Much of the research is focused towards building such a machine. Vilbrant at. el. [14] describe fabrication system and manufacturing framework that they termed “Universal Desktop Fabrication” (UDF). In their work, the researchers portray a vision of a fabrication machine that can produce functional objects in any arbitrary shapes.

Among other capabilities the machine will also be able to produce functional electronic objects. One of their examples is the ability to “print” a cell phone, including the batteries, or a robot that can walk out of the printer by itself, right after the printing is over.

The ability to manufacture electronic devices in one process by using a single machine has many advantages. One of the most important advantages is the elimination of the assembly process. Today, almost all electronic devices are manufactured and assembled in the Asia, taking advantage of the low labor force costs. Parts of the product such as the enclosures, PCBs and buttons are manufactured separately and then shipped to an assembly house where they are assembled together. Typically, given the amount of parts and the complexity of the geometry, assembly processes are hard to automate [15]. In addition, it is difficult for the assembly process, which becomes inflexible in large quantities, to support the rising demand for products variants [16].

Therefore, once the electronic products will be digitally fabricated in one single process, there will be no longer a need for an assembly stage done by workers. A Machine will be able to produce the same part with the same cost anywhere, so products could be manufactured close to where they are needed. These machines could easily produce variants of products and not necessarily the same exact copy each time. In addition,
since digital objects can be fabricated on demand, the needs for keeping inventory and stock will decrease, which will also substantially decrease the production costs.

The technology for making a machine which will enable the production of 3D objects comprised of electronic circuitry and functionality, is still years away [13]. However, the technology for making two dimensional objects comprised with circuitry and components has been around for many years, this is the PCB technology.

In this research I am proposing a new design concept for producing electronic devices that will be fabricated as two dimensional sheets and then manipulated into a three dimensional form by folding. The idea is to harness existing machines, tools, software and workflows, for creating electronic products that are composed entirely from PCBs without any enclosures.

Designing such PCBs will make the work of PCB designers even more challenging than it is now. Today, those designers need to design the layout and traces of PCBs, sometimes with many layers, and decide on the location of components based on electronic properties and the needs of the product. Usually their goal is to minimize the surface area of the PCB as much as possible, or design the layout (outer contour) so it will fit the plastic enclosures that were designed by the industrial designer that designed the product. Using the PCB as structural material mean that PCB designers will need to design not only the circuit itself and layout, but also design the 3D shape that the PCB will be folded into and also the electronic system that will support the folding by guiding the user and/or verifying the folding state of the board.

### 3.2 Rigid Origami and Origamizer

A source of motivation and inspiration for me is the work of Tomohiro Tachi from the University of Tokyo, Japan. Tachi’s work focuses the mathematical, aesthetical and functional aspects of origami. In particular, I was inspired by Tachi’s Rigid-Origami [17] and Origamizing Polyhedral Surfaces [18] research work.
Rigid origami is piecewise origami that is composed of facets with flexible hinges between them that allow continuously transformation without deformation of each facet (see figure 3). These structures have some engineering application, especially in designing deployable structures with stiff panels that have just one degree of freedom. In the mathematical context of Origami, the material’s thickness of the folded material is calculated as zero, however in reality, the thickness of folded materials is a factor, especially when rigid and stiff panels are needed. In his work, Tachi proposes a geometrical method for implementing rigid-origami for materials with thick panels that have a constant thickness, and also demonstrates architectural-scale applications [17]. Rigid-flex PCBs can be designed by rigid-origami principles. This will add a functional dimension to such mechanism.

Figure 3- Twisted and Curved Miura-ori, Rigid Origami -Tomohito Tachi

In Origamizing Polyhedral Surface [18], Tachi presents an algorithm and software that calculate and generate a two dimensional crease pattern (folding pattern), for folding a given polyhedral surface out of paper, without cutting the paper in the process. The input of the software, called Origamizer (see figure 4), is an arbitrary polyhedral surface (an STL file) and output is a folding pattern that can be printed and folded to make a physical sculpture in the geometry that was uploaded to the program.
The research shows that in theory, almost any three dimensional geometry can be generated by folding a two dimensional sheet. In practice, the actual folding is an extremely time consuming task (the bunny in figure 4 took about 10 straight hours to fold by the hands of a folding master). In addition, giving to the amount of folds, folding of such a piece demands special paper that is thin yet able to keep its mechanical position after folding. Therefore, it is difficult to implement electronic circuits with this method of form generation.

![Figure 4](image)

*Figure 4 - On the left is the interface of the Origamizer software, showing the CAD file and the crease pattern. On the right is the physical sculpture of a bunny that was folded using the pattern.*

### 3.3 PCB Creations

Lastly, a source of inspiration and motivation for me comes for the work of the artist Steven Rodrig from Long Island City, New York [19]. Rodrig terms his work – “PCB Creations”. He is using recycled and re-constructed PCBs to design and build sculptures of insects, flowers, still life and city-scapes. His method is to cut PCBs from old computers and televisions and use the parts and components that are on those PCBs to help shape the meaning of the sculptures (see figure 5). I was drawn to the surprising aesthetic and design language of Rodrig's work. We are used to seeing PCBs just as the inside of products once they get broken or getting fixed, however in those sculptures, the visual effect and the richness of details turn the PCBs into interesting and appealing artifacts. In my opinion, his work proves that PCBs themselves can actually look attractive to stand alone as the final design with no need of plastic enclosures.
In Rodrig’s work, the PCBs are being used as raw material, and are not functional. I was motivated to explore what if those objects could be more than just sculpture and carry a function as well, for example be able to sense or display information.

Figure 5 - There’s No Data Like Home - By Steven Rodrig
4. Aims and goals

In this research I am proposing an alternative paradigm for the fabrication of electronic products. This approach is not likely to replace the current paradigm of assembling products from PCBs and enclosures in the near future. Products made with enclosures are smooth, might have an organic shapes, can be colorful and have textures. On the other hand they demand an assembly process and are difficult to be customized or altered if variants are needed.

My goal in this project is to provoke thought about digital fabrication of electronic products and to promote the idea of materials with embedded electronic functionality. In the future, technologies that are under research today such as stretchable electronics [10], 3D printed boards [11] and embedded components inside the material thickness of the PCB [12] will be available. These new material properties and fabrication technique will introduce new possibilities for electronic functional skins that can be folded or manipulated in various ways, and might replace in some cases products with plastic enclosure, for a cheaper, sustainable product that is easier to produce in terms of time-to-market.

My primary interest and aim in this project is to explore the interaction and fabrication possibilities of electronic materials. I am interested in the user experience of folding and unfolding of PCBs and the possibilities for new functionalities and interactions that can be achieved. Specifically, in this context, my aim is to demonstrate products that can be flat while not in use, and can be folded into 3D objects when needed. Furthermore, I would like demonstrate the concept of multiple functionalities of folded electronic products; products made of a single PCB that can be folded into more than one configuration, while carrying the electronic functionality for each of those configurations. In addition, I would like to demonstrate the way the materials itself can guide the user on the current folding sequence by embedding light signals and sensors into the material.
5. Foldable electronics - State of the art

PCB Origami is a repeatable, interactive and engaging approach for folding PCBs into functional products. Below is review of manufacturing technologies and research projects that incorporates folding of electronic materials.

5.1 Foldable electronics as a manufacturing technique

In the electronic industry folding PCBs is used mainly as a manufacturing technique for volume optimization of products such as the digital camera, where a generic form factor and an interface in more than one face of the product are required (see figure 6). The flexible PCB replaces wiring and allows the creation of one PCB without any ports and connectors [16]. In addition, folding flexible PCBs can be used to enable high density packaging, small footprint and volume optimization of power electronic components such as transformers [20]. A recent example of a product manufactured by folding PCB is a project called “Nanolight” [21]. In this project a rigid-flex PCB with embedded LEDs is folded and inserted into a light bulb socket to replace traditional light bulb (Figure 6).

![Figure 6- Flexible PCB as manufacturing technique for volume optimization (A) and 3D structures (b)](image)

A novel folding-based fabrication method for manufacturing millimeter scale electronic robotic systems is demonstrated in the Monolithic bee (Mobee) project by Sreetharan et. al. [22] This method is inspired by pop-up books and loosely based on traditional fabrication technologies of PCBs. A laminated PCB-like sheet is fabricated and micromachined using a laser cutter. The Machined sheet is then mounted onto an actuated platform that folds the structure into a 3D geometry similar to a pop-up book. Solder
material is used to lock folded hinges, and then the structure is micro-machined again to extract the final product.

5.2 Actuated Origami

The integration of electronic circuitry with Origami folding was researched mainly in the context of actuated systems that generate motion, shape changing and locomotion. Those systems mainly use Shape Memory Alloy (SMA) for actuation (the use of SMA in context of PCB origami is presented in this work in case study 5). SMAs are metals that can be trained with heat to remember certain geometry. After deformation of the metal it can go back to its trained position by heating it to a critic temperature that is lower than the temperature that is needed for the training [33]. Heating the SMA is done by running current through the material, thus electronically controlling the actuation.

Hawkes et al. demonstrated a self-actuated surface called “Programmable matter by folding”. This surface is based on universal crease pattern geometry that is composed of right angle triangles. The surface is embedded with traces and SMA actuators are embedded within the hinges. Depending on the input, the surface it can automatically folds itself the shape of a boat or an airplane (figure 7) [23].

An artistic example of actuated Origami is the Electronic Origami Crane and animated vines by Qi et al. [24]. In Electronic Origami Crane, SMA is embedded in the wings of a traditionally origami crane that is folded out of paper. PCB is attached to the paper by gluing copper tape that was cut using a vinyl cuter and soldering components onto it.
The SMA attached to the paper that is folded into the wing by sawing thread that keeps the SMA in place. When current is applied the SMA shrinks and forces the paper to bend, resulting a flipping motion of the wing. A more dramatic effect is presented in the “animated vines” projects. SMA is attached similarly to long strips of paper. When the SMA is actuated the paper strips curl and bend in inorganic like motion. Given to the length of the paper, the motion is dramatic and noticeable.
6. Methodology

The design of a PCB can be considered as a logical puzzle. The PCB is composed of many traces that need to be connected across the board without crossing each other. In order for the traces not to cross, often the components are needed to be placed in specific locations and orientations, or more layers are added to the design.

Designing foldable PCBs for this project was even more challenging because two important factors were taking into account. Firstly, the PCBs are needed to be folded, that affected the location of components and traces. And secondly, the appearance of the PCB was important for me. I made an effort to design the traces and components on the PCB in a symmetrical and organized way with relation to the overall two dimensional layout and the three dimensional form after folding. From the point of view of a designer, once the PCB is the product itself, the traces and components becomes the graphic facade of the products. Those traces need to be designed not only as functional pathways for electrons, but also as visual elements that are inseparable from the overall aesthetics of the product.

6.1 Conductive connection

In order to make the interaction with folded material possible I developed the concept of conductive connections for temporary connections of different edges of the PCB. Conductive connections are mechanical connections that can give feedback to a microcontroller on board the PCB if a connection is established or broken. Those connections can be easily connected or unconnected by the user. Conductive connections allow creating objects that can be aware to their own folding state and act accordingly.

6.1.1 Selective fused solder connection

Solder is the most common technique for connecting components to a PCB. This is a fast, effective and robust way to make connections that are usually permanent. Other than connecting components, solder material can be used for connecting edges of PCBs and creating rigid structures. Although it is possible to undo solder connection, this
process requires a soldering iron, and sometimes cooper braid for absorbing the solder material. Standard soldering is therefore not suitable way for creating connections that can easily be undone by the user.

![Low temperature solder pads](image)

**Figure 8 - Selective fused solder connection sequence**

However, by using low temperature solder material it is possible to create connections that can be fused automatically and be easily established or undone by the user. Inspired by fused clutch mechanism [27], I developed a low temperature fused connection for connecting together edges of PCBs. Low temperature solder material is deposited on copper pads on the PCB. A resistor is positioned next to each of those pads. Running current though the resistors heats the resistors up and melts the solder material on the pads. The system works as follows: In the folding process the user position two edges with solder pads one on top of the other so that the pads are touching. The microcontroller onboard the PCB senses the connection by running current through the pads. If the connection is correct according the folding sequence, the microcontroller heats up the resistor. After few seconds the solder material melts and the heating stops, then the solder material cools and the two edges of the PCB are connected (see figure 9). Undoing the connections is done by pressing a button onboard the PCB that signals the microcontroller to heat the resistors again, allowing all edges to disconnect (See electronic schematic in appendix A).

After making a few prototypes and testing of this concept I ran into some problems that eventually made me decide to pursuit other alternatives for conductive connections. The biggest problem was the heat that was generated by the resistor was too high and dangerous for touch. Also, the fusing process (heating the resistors and waiting for them
to cool off) took just few seconds but in case of a product with multiple connections this time is too long. Lastly, the low temperature solder material I was using oxidized after few cycles of heating and cooling, and needed to be replaced.

![Selective fused solder connection prototype](image1)

**Figure 9** - Selective fused solder connection prototype

### 6.1.2 Magnetic connections

Magnetic connections are less robust than thermal or mechanical connections yet they are the simplest and fastest way of connecting edges of PCBs for users. I used nickel plated neodymium disc magnets in diameter of 1/8 in (see figure 10). Those magnets are electrically conductive and have pull strength of 0.6lbs. Press-fitting the magnets into plated holes of a PCB provide mechanical fixture and electronic connection at the same time. Another method for connecting the magnets to traces on the PCB is by gluing the magnet using conductive epoxy.

![Magnetic connection- the magnets are glued to the traces with conductive epoxy](image2)

**Figure 10** - Magnetic connection- the magnets are glued to the traces with conductive epoxy
6.1.3 Momentary connections

Momentary connections are simple connections that can be part of a mechanical snap-fit or can stand alone. Those are basically exposed conductive pads that touch each other in the process of folding. In this case the connection itself is only electrical and not mechanical. The shape after folding is maintained either by using a material that can be deform by folding like paper, or by incorporating the pads into mechanical press fits. Differently from other connection mentioned above, in this case the conductivity is not necessarily maintained after the first contact was made. Therefore when using this method, it is not possible for the microcontroller to know if the connection breaks, only if it was once established.

6.2 Mathematical principles – Alexandrov’s Theorem

The question of which 2D polygons can be folded into a 3D convex polyhedron was a subject of investigation since the era of the great Greek mathematicians, and up to these days in cutting edge geometrical research. A polygon is defined as a planar shape with straight boundary edges, and a polyhedron as a three dimensional shape with boundaries that are composed of flat polygons. A convex polyhedron is a polyhedron without indentation or dents, with vertexes that are all convex (a total angle at a vertex is less than 360°) such as a cube, tetrahedron, or icosahedron (soccer ball).

A Russian mathematician Victor Alexandrov published a theory on folding convex polyhedral in 1941. Driven from his theory is the proof that every convex polygon can be folded into an infinite number of convex polyhedral, as long as three rules, that are termed Alexandrov gluing, are satisfied [27]; (1) every point on the primitive of the polygon must be matched to another point, meaning all the entire primitive must be part of the folding. (2) Each vertex of the polyhedral must be convex (that is what makes the polyhedral a convex polyhedral). And (3), the result of folding is a geometry that theoretically can be deformed into a sphere, meaning it cannot be a twisted shape or a shape with internal holes like a torus [28].
Alexandrov’s theorem is the foundation of the folding of the Latin cross shape that is presented in case study 1 (page 41). In addition, experiments of folding a rectangle polygon shape with a grid of 3 by 4 squares were tested and are presented in figure 11.

![Image of folded shapes]

**Figure 11** – Six different polyhedral are folded from a rectangular polygon with a grid of 3 by 4 squares.

### 6.3 Software

The main challenge in designing foldable PCBs is to integrate the design of the electronic circuit with the design of the physical three dimensional forms and its flat state. Software for PCB design generates two dimensional output files, and doesn’t allow any 3D manipulation. An integrative approach was therefore needed for using both CAD software and a PCB design software.

The process of designing the geometry of the PCBs started with cutting and folding physical paper and card board mock-ups. Then, selected designs were modeled in SolidWorks CAD software. Connection tabs or slots for magnet were added to the design and then the 3D shapes were un-rolled into a flat state using Sheet Metal feature. This feature allow un-rolling of a 3D geometry by selecting a fixed surface and by selecting bended edges. The software calculate the two dimensional geometry while taking into account the material thickness and bend radius.

Software for unrolling 3D objects into a flat geometry is Papekura Designer. This software is used mainly for DIY projects of making origami sculptures of complex shapes. The software un-roll the design based on open edges that are selected in the
graphic user interface and automatically attach tabs for gluing on those edges (figure 9).

The output of the software is a 2D file that can be printed and folded.

Figure 12 - screenshot of 3D design and a 3D layout in Papekura Designer software

The electronic circuits were designed in Eagle software. After designing the schematics of the board, the traces and location of components where integrated with the two dimensional file produced by the CAD software.

6.4 Prototyping techniques

For initial prototypes, traces were cut on the vinyl cutter and then glued on paper. Following, I used rapid prototyping services of ink-jet printing of conductive material [25] that allows printing copper on Polyethylene Terephthalate (PET) material from a digital file. For reinforcement of the PCB I used acrylic plastic that was cut on a laser cutter. I developed a technique for precise lamination of the PCB with the plastic; the rigid shapes of the plastic were connected with small links to each other and to a supporting frame, this allowed handling the rigid shapes as a single integrated part. The PCB was laminated between the layers of the plastic and positioned using pegs that ensured a correct positioning of the PCB in relation to the plastic reinforcements. After the lamination was done, the small links were broken, allowing removing the final PCB from the supporting frame and the gaps between rigid areas to become the hinges for folding (see figure 13).
A flexible PCB is laminated between two sheets of machined acrylic plastic (A). The PCB in the shape of a Latin cross is connected to the frame with small links that can later be broken to extract the shape (B).

6.5 FR1 PCB with slits

A method of bending stiff and rigid sheets of material such as wood [26] is cutting a pattern of slits perpendicular to the bending direction. I was experimenting with bending PCBs made from FR1 material in 1.6mm thickness. This is paper based copper plate material, used for prototyping of PCBs, which is completely stiff and cannot be bent. A pattern of slits was milled with a Modella CNC milling machine and, in addition, copper was removed in specific areas that divided the pattern into three separate areas that are insulated from one another. The result was a PCB that can be bent with slits that perform also as traces for conducting current. Later, a bending sensor was incorporated and LEDs and resistors were soldered onto the PCB. When the PCB was bent, the LEDs blink speed and light intensity corresponded to the amount of bending (figure 14).
Figure 14 - Bent PCB with slits that perform as traces
The core concept of PCB origami is digital fabrication of functional electronic products that are made by folding electronic materials – PCB, into 3D objects. The fabrication process of those products will be based on today's existing approaches, tools and workflows of manufacturing PCBs, but differently from today, the PCBs will be the finished product and will require minimal manual or robotic assembly stage. Moreover, this fabrication process will allow creating products with variants, meaning the PCBs that are being produced can defer in size, shape and functionality. Products will be mass-customized, allowing users to purchase products that fit their needs, preferences and ergonomics.

This research proposes an interactive and engaging folding process for turning 2D PCBs into 3D products. The user of will be the one responsible to folding the product into the correct configuration. This approach will require less labor on the side of the manufacturer, and will allow manufacturers and distributors to ship products in flat envelopes, and save on shipping costs and inventory space. Users will take an active part in manufacturing of their products, and have an engaging experience of interacting with materials.

On top of that, the folding the product can be repeatable. The user can keep the product flat and fold it only when it is needed. This feature is valuable especially for computer accessories that are on the go such as mice, cameras and game controllers. Flat products can be kept in an envelope, stored between pages of a notebook or be integrated in covers of tablets or cases of lap-tops.

In this work, several aspects of the concept of PCB origami were examined and case studies were demonstrated: PCBs that can change their shape to fit a specific function, PCBs that are embedded with information on the correct way and sequence for folding them, PCB Origami products that can be customized to fit a specific user, and bending of
PCB for creating actuated sculptures. Below are detailed explanations of each of those aspects. Case studies are presented in chapter 8.

7.1 Computer-Aided approach for folding Electronic Devices

Since the invention of paper people folded it to generate 3D objects and sculptures and the art of Origami was created. At first, the knowledge of how to fold paper passed verbally from one generation to another but today numerous books and instructions for guiding users can be found. By using PCBs as the medium for origami folding it is possible to incorporate the folding information within the material itself and in addition create an interactive folding experience.

![Figure 15 - A typical Yoshizawa-Randlett folding diagram (A) and a typical mountain valley diagram (B). Blue and red lines represent mountain and valley folds respectively. The shown diagram is for folding a lizard.](image)

Origami can be interpreted as a digital form-generation fabrication process. A single sheet of paper can be folded into numerous shapes depending on folding sequence and crease positions [35]. Once the paper is folded it can be unfolded and folded again into a different shape. The physical (material) properties of the paper support its ability to fold and to unfold [36]. However, paper in itself is a passive material in the sense that it is not adaptive or responsive to external constraints, and the process of folding it is not interactive. The feedback one receives from folding paper is in most cases a visual one, comparing the physical sculpture to the drawing in the folding diagram.
Two main methods exist for guiding users in the process of folding a sheet of paper. They include the implementation of a folding diagram based on the Yoshizawa-Randlett system [37] and the use of a mountain valley diagram [38] (figure 15). The Yoshizawa-Randlett folding diagram preserves the “digital” nature of paper-folding; according to this method a diagram is used to fold an origami sculpture. Once unfolded, the same sheet of paper can be used to fold another origami sculpture using a different diagram.

On the other hand, the Yoshizawa-Randlett folding diagram is not direct in the sense that it only provides a guiding external representation, and relies merely on the visual representation of the fold [37]. Printing a mountain valley diagram on the paper can be considered as a direct approach for guiding the user in the folding process, but it is not digital. Once the diagram is printed, it can only lead to the folding of a single shape.

In research, Interactive Origami folding processes have been explored by representation systems that are external to the folding substrate (paper). The “origami desk” by Wu et. al. [39] is an interactive installation that guides its users by projecting videos and images on the top of the working area. The system uses “hot spots“ on the projected area as well as field sensing arrays, to collect inputs from the user and allows him to fold in his own pace.

Another system, which uses a camera, is given by Kinoshita et. al. [40], where the silhouette of the folded Origami is analyzed for estimating the folding state. Both systems are based on external projection or imaging devices for receiving or transmitting information of the folding procedure.

Unlike paper, which is homogenous material with fixed properties along the material system, PCBs are composites that are not homogenous and their structure and properties can vary. By using PCB as the medium of folding an interactive folding experience can be created without using external imaging systems. Conductivity, output devices such as Light Emitting Diodes (LEDs) and microcontroller computation can be leveraged for providing user guidance and verification of the folding procedure as
compared to the planned sequence. Conductive connections are used to digitally verify if the correct fold was established and the next step in the sequence can be presented.

Case study 1 (page 41) describes two unique verification/evaluation strategies and fabrication techniques for creating and folding electronic materials.

7.2 Digital fabrication and customization of foldable electronic products

Digital fabrication tools enable the creation of physical objects out of digital files. One of the biggest advantages of these tools over mass manufacturing tools is their ability to produce many different parts in the same cost as making them identical [41]. This allows creating products that are customized by the user preferences or needs in contrast to the mass customization approach of same product for every user. One of the most prominent applications of the customizability of digital fabrication products is in the medical field where products need to vary depending on the body of the patient. Numerous examples of the customized medical application had been researched and commercialized. Today digital fabrication using 3D printing is being used for dental implants [42] and prosthetics sockets are designed based on MRI scans of limbs [43].

However, there are only a handful of research examples for digital fabrication and customization of commercial electronic products. The main reason is that in general, electronic products demand a complex fabrication process that includes fabrication the electronic material (PCB) and the structure (usually encloses) of the product. Mellis [44] proposes an open source fabrication approach for customizing electronic products by combining a custom design of the PCB and digital fabrication of the enclosures with technologies such as 3D printing and laser cutting. This approach uses the mass manufacturing paradigm of the design of electronic products with functional separation of electronics and structure. The design of variants in this approach is challenging because changing in the enclosures, like scale or proportion, might result in a change of the electronics and vise versa.
An integrated approach for fabrication and customization of electronic sensors is presented in the work of J. Leigh et. al. [45] that developed a conductive material called “Carbomorph”. This composite material can be used as filament for low-cost 3D-printers. When this material, along with a conventional non-conductive filament, is used in a dual head 3D printer, 3D objects can be produced that have incorporated electronic traces that function as pressure or capacitive sensors. This work is an example of functional integration of structure and function. However the functionality of products that are produced with this technology is limited because, as for now, it is a problem to incorporate electronic components that are essential for complete electronic functionality such as micro-controllers, capacitors and more. Those components need to be external to the products.

The PCB origami concept proposes an alternative approach for fabrication and customization of electronic devices; products are manufactured in one process without a need for integration of materials and processes. Also, this concept allows full electronic functionalities, same as conventional PCBs.

Cases study 2 (page 46) focuses on two electronic products, a computer mouse and a game controller and the process of customizing it to individual user physical dimensions.

7.3 Shape changing user interface by folding

Throughout the history of product design, products were traditionally designed to serve a dedicated single function whereas their shapes were designed to support their functionality [46]. Up until recently this principle held generally accurate for electronic devices as well. A phone, a camera and a music player all had a specific iconic shape that evolved over the years to suitably serve the function of the product, in terms of comfort, ease-of-use, ergonomics and user interface. Today, however, with the introduction of touch screen devices such as smart-phones and tablets, many of those functions are embedded within a single form factor, usually a flat rectangle. The smart phone for example serves as a phone, a camera, a music player, a flashlight and more, and the selection of the desired functionality is implemented with a graphic user
interface (GUI), by touching the appropriate icon on the touch screen. Furthermore, one may claim that the flat rectangle shape of the phone has nothing to do with the appropriate way of holding a camera or a flashlight. The rigidity of electronic products limits their affordances and usability options [47].

![Figure 16](image)

**Figure 16- A diagram of the suggested evolution of electronic products**

In contrast to these products, PCB origami products could be folded in different ways in order to change their form factor to fit a specific function. PCB origami products will be able to detect their own shape and independently assign different functionalities to buttons as well as enable or disable electronic systems within (figure16).

Several material based approaches for shape-changing interfaces have been studied including inflatable interfaces [48], utilizing shape memory materials [49] and bending of thin films [50, 51]. Another approach for form deformation is presented in the ShapePhone project by Follmer et. al. [52], where the principle of material jamming is being used to change the rectangular shape of the phone into the shape of a watch, controller and remote control. Users deform the flexible material of the phone and by applying vacuum the shape becomes rigid. While this approach produces objects that are organic and smooth, changing the form is dependent on using an external air pump and valves. In addition, the detection of the shape is done by an outside imaging system, and is not inherent in the physicality of the objects itself.
In contrast to the above approaches, the concept of PCB origami suggests using a PCB as the product itself, and folding manipulations as a shape changing technique. By folding the PCB the user can control the appearance, ergonomics and electronic functionality of products, all at the same time. Case study 3 (page 54) demonstrates an example of this concept— a 2D PCB that can be folded into computer mouse or a game controller.

7.4 Bending and curved folding of PCBs

PCBs are composite materials made from conductive and insulative materials. The conductive material is thin layer of conductive metal, usually copper. Many types of materials are being used as insulative materials for PCBs: Cotton paper and epoxy (FR1), fiberglass and epoxy, or thin films of Kapton [53] material. The physical properties of the PCB are determined in most cases by the physical properties of the insulative material. In case of rigid material such as FR4 – a woven fiberglass cloth with an epoxy resin binder, the PCB will be rigid, and in case Kapton film is being used, the PCB will be flexible.

Other insulative materials for PCBs include paper and Polyethylene terephthalate (PET). Those are flexible materials that allow different kinds physical manipulations in transforming their 2D geometry into a 3D shape. Bending of paper based PCB is demonstrated in case study 5, where the springiness property of the paper is leveraged for creating actuated sculptures. Curved folding of PET material using perforation is demonstrated in case study 4 (page 59).
8. Case studies

8.1 case study 1: PCBs with embedded folding information

Two examples demonstrating the concept of guided folding using PCB as the folding material are presented below. Each of these examples uses a different type of origami logic, a different material and different input and output method.

The approach taken in this work is the creation of an integrative system that uses both software and hardware. In this material-based approach [1], both the software and the hardware can be used as input and output in the folding process. The hardware refers to the folded PCB, which communicates with software installed on the computer. The folded PCB is embedded with LEDs and conductive connections. The LEDs are digital markers, indicating specific locations on the surface that are relevant for the current folding action. Conductive connections are being used to verify if a connection was engaged, by checking the conductivity between two pads that are assumed to be connected. The conductive connection can be either momentary—two electrodes that touch each other—or temporary—creating a reversible bond that supports the structure of the folded piece.

![Figure 17](image)

**Figure 17** - A Latin cross polygon (A) can be folded into a pentahedron (B), or a cube (C).

The first example is based on the “Metamorphosis of the cube” by Demaine et. al. [54], which demonstrate the idea of edge-to-edge gluing and folding of a flat polygon into convex polyhedra. In this example, a flexible PCB in the shape of a Latin cross polygon is embedded with LEDs and connection pads. The polygon can be folded into a cube or a different polyhedron depending on the sides being glued (figure 17).
Figure 18 - A set of tabs and slots have been placed on specific sides of the Latin cross polygon. The tabs are marked with letters and the slots are marked with numbers. The lists show different pair assignments, creating a pentahedron or a cube. A led is placed next to each tab or slot.

In this example, tabs are attached slots are removed from some of the sides. For each shape that can be folded, a different set of tabs and slots must be connected in order to fold the shape (Figure 18). The folding process begins when the user selects the shape he wishes to fold with the software. Then, depending on the shape selected, the first set of LEDs blinks, marking the specific tab and the specific slot that needs to be connected. After the connection is made, the next set of LED blinks and the process continues until the folding is complete.

The second example uses software and paper covered with conductive pads in order to guide the user and verify the folding. The folded paper is a lamination of three layers of thin sheets of paper. The middle layer is being used as the circuit board. Copper stickers are attached to both sides of the paper (Figure 19). The other layers are used for masking. Holes are cut in the outer layers using a laser cutter. After precise lamination of the sheets, conductive circular stickers are glued on top of the holes and touch the circuit board on the middle layer.
By connecting the paper to a microcontroller it is possible to know when two pads are touching each other. Each fold is perpendicular at the midpoint to the imaginary line that connects between the two pads (Figure 20). The user is guided through the folding process using the software. The software illustrates the folding with the circular pads on the paper as references. By checking conductivity between two pads it is possible to verify if the fold is correct, and move on to the next fold.

In order to test the interaction and the quality of the guidance, a small user study of 10 participants was conducted. Participates were asked to fold the Latin cross shape into a polyhedron (figure 17A), once guided by folding diagram and a second time using the LEDs. The results show that folding the shape using LEDs for guidance was three times faster than when a folding diagram was used (Table 1). On average, users spent 65 seconds folding the shape when guided by a diagram compared to 24 seconds when guided by LEDs. Participates reported a joyful experience, and communicated that they were more efficient and engaged in the process of folding. Folding using the diagram...
was described as “complicated” and “frustrating”, while folding with guidance from LEDs was described as “super-obvious” and “easy”. Even though, some of the participants liked the puzzle element of folding using a diagram and felt that the guidance from LEDs disturbs the solving process [53].

Figure 20 - For each fold, a crease line is perpendicular at the midpoint to a line between two dots (a). The microcontroller can sense when two dots are touching (b), then signal the software to proceed to the next fold. In this example the paper folds into a boat, after 12 steps (c).

The tabs and slots method for “gluing” edges seemed to work well in the physical model of the Latin cross; the folded polyhedral shapes were solid and rigid. Beside the electronic contact property of the tabs and slot, its geometry also provided a mechanical connection that was helpful in the folding process. However, using tabs and slot limited the number of polyhedral shapes that are possible to fold. In “Metamorphosis of the cube”, the Latin cross polygon is folded into five different polyhedra: a cube, a flat polygon and three convex polyhedra. In the physical model of the cross only a cube and a single other polyhedron can be folded. The reason is that folding other polyhedra, would require many more hinges, tabs, and slots.

In the prototypes, copper tape was used for creating traces for the PCBs. As a result of repeated folding and unfolding the copper traces eventually ripped, creating a failure in the PCB. The number of folding and unfolding that could be done is depended mainly on the width of the trace and the bending radius. In the first example traces were 2mm wide and the bending radius of traces was minimal - almost same as the thickness of the flexible PCB. Traces started to rip after about 40 cycles of folding and unfolding. In
The second example, traces performed better. The traces were wider (5mm) and because the PCB was laminated between two layers of paper the bending radius was greater (The radius is calculated by the width of the flexible PCB plus the thickness of glue and paper sheet). To improve the performance of the traces several approaches can be taken such as enlarging the bending radius of the fold, or using a thinner layer of conductive traces. Also, applying a slitting pattern similar to the one presented in section 6.5 can also reduce the tension in the material and prevent rips.

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8.2 Case study 2: A workflow for customization of foldable electronic products

This case study describes a workflow of mass-customization of foldable electronic devices based on a physical scan of user’s hand, which is done using simple sensory devices that can be found in almost any home. An example of an innovative product was selected: a detachable iPad cover with internal piece that can be removed and be folded into a game controller. The game controller can be used as an input device for the tablet and as a protection cover when the tablet is not being used or on the go.

![Image of controller iPad Cover]

For this case study a circuit board with ten capacitor sensors, an accelerometer, button and a LED was designed.

The capacitor sensors are arranged in two groups of four for each thumb (up, down, left and right buttons) and two capacitor sensors on the front of the controller for the index fingers. Capacitor sensors are printed as conductive pads on the PCB and practically have no thickness. Other components on the PCB have a maximum height of 1.3mm;
this allows hiding the components inside the material thickness. The PCB itself is inkjet printed on a flexible PET film using the services of “Inkjet flex” [25]. On the flexible PCB, components are soldered, and plywood in thickness of 1/8 in is laminated to reinforce rigid areas, and allow hinges to form between them. Both the controller and the cover are embedded with magnets. The magnets on the cover are attracted to the magnets on the controller in its flat state, keeping it in place and preventing it from folding. Once the middle piece is removed from the cover by the user, the same magnets are being used to keep the folded 3D shape together. The cover is connected to the iPad with a standard cover hinge, for detaching it easily when the cover is unneeded.

Unlike mass manufacturing game controllers that have one size and shape for all users, the foldable controller is examples of a product that can be customized to fit a specific user. In addition to fit, the functionality (number of buttons) and style (image that appear on the product) of the controller can theoretically be customized. The fabrication of the product in 2D along with a sophisticated flexible design of the CAD file (like presented in this study case), allow a serial fabrication process of customized products, or in other words mass customization.

Mass customization is defined by Piller [56] as a co-design process of products and services within a fixed solution space. Customization can be carried out with regard to three aspects: style, functionality and fit. Out of the three, the ability to tailor a product according to the body dimensions of the customer is the strongest argument for in favor of mass customization [56]. However, it is also the most difficult one to achieve. Scanning devices such as 3D scanners, MRI or CT have poor accessibility for the average user and also demand a skilled professional for their operation. Several examples of online customization of digitally fabricated products based on style and functionality exists such as Nervous System [57] for jewelry, and MakieLab [58] for toys, however, making online customization tool based on fit is more challenging. A conventional approach for customization based on fit is presented in a case study of customizing a garden fork handle by Campbell [30]. In the case study, the end user models the shape
of the handle using air-drying modeling clay. Later, the modeled clay is being 3D scanned using a 3D scanner that generates a point cloud data. The cloud of points is then translated into a solid model, in a process that includes patching and refining the model. The 3D model can then be fabrication using 3D printing or milling machine. The process presented in the case study of the fork handle is a long and complex. In order of products to be mass customized a simple process is needed.

The concept of customizing foldable products presented here, exploit sensory devices that usually exist in every home to obtain information about the dimensions of the user body. Making the processes of customization simple and effortless for users can contribute a lot to the success of such operation.

The workflow begins when the user log in to a website and is asked to scan his hand using a document scanner. A scanner was selected because it gives and accurate scale of the image, where each pixel in the image can be translated into physical distance by multiplying it with the image Dots Per Inch (DPI). In case a document scanner is not available, this same principle can be implemented using a photo. A reference object with known dimensions, like a coin of quarter, can appear in the photo and be used to scale the image. Besides customization based on scanning, the user can also customize the appearance of the product by choosing a material that will be laminated on the PCB or an image of his choice. Software analyzes the image of the hand and extracts the dimensions of length of fingers and the height and length of the palm. This information is then transferred into parametric CAD model that updates according to the given dimensions. The CAD software automatically generates a production file that is sent to the manufacturer. After the product is manufactured it is shipped to the user in a flat envelop, ready to be folded and used.

Designated software was developed to measure the length of fingers and palm based on an image of a hand. The user is asked to scan his right hand with spread fingers. After the image is generated, an algorithm detects the skin regions using the Skin Probability Maps [59] method. At first the algorithm uses bootstrapping to get an initial skin map
based on prior knowledge of skin colors, and then refines the result for better accuracy using the skin histogram in the image. In the next stage the contour of the hand is extracted and re-sampled to three hundred points. Based on established research into salient points in shapes [61], the contour is analyzed to find points of "curvature extrema" - point on the curve where curvature or direction changes dramatically.

![Put your right hand with fingers spread on the scanner](image)

**Figure 22 - customizing software GUI**

Examples of such points are the tips of fingers or the connection point of two fingers. By comparing the curve to a known typical structure of a hand, using a variant of the Smith-Waterman sequence alignment algorithm [62], it is possible to define segments of the curve that define each finger – one that defines the pinky, another that defines the ring finger and so forth. A Principal component analysis (PCA) algorithm [60] is used in order to find the main axis of each finger. Either the valley points between the fingers (if one is available) or a curve-point that crosses the perpendicular line to the major finger axis, determine the base point of the finger. From that base point the distance to the tip of the finger is calculated and used as the length of the finger. The finger width is calculated by drawing a perpendicular line to major finger axis on a point that is 4/5 length of the finger. The perpendicular line is limited by the contour of the finger. The palm is calculated by connecting the connection point of the middle and ring fingers to
the base of the palm. The base of the palm is found by walking the contour from the bottom of the image going up, looking for a sharp increase in the width of shape, which coincides with where the wrist ends and the palm starts.

The software calculated the actual length in millimeters by multiplying the length of each dimension with the DPI of the picture (obtained from the scanner or by calculating the known dimensions of the reference object with its measurement in pixels). The lengths are then exported as a table into an Excel file that is used by the CAD software.

![Hand Scan](image)

**Figure 23**-typical scan of a hand. The yellow line marks the finger contour, the red line the thumb contour. Blue lines are the dimensions that are extracted from the hand. Pink circles mark the curvature extrema points on the curve.

Parametric CAD files were design for a game controller and a computer mouse in SolidWorks CAD software. The files use a Design Table tool provided by the software package that enables creating a parametric model with relations between dimensions in the model and information in an Excel spreadsheet file. Each row in the spreadsheet is
generated by the hand scan software presented above, and represents the set of fingers and palm dimensions of one single user, and in the CAD file each row is translated to a single configuration of the product (figure 25). The scale, dimensions and proportions of the controller and mouse changes according to the current configuration that is shown on the screen. The result is one file that can accumulate many variation of the same product.

Figure 24 – Mockup of a game controller was built in order to test the relation between length of fingers and palm to the
size and proportion of the controller (A), and then implemented in a diagram and CAD model. A mouse was designed based on an ergonomic diagram (C). A screenshot of the CAD model of a mouse (D) - dimensions that are drawn from Excel spreadsheet (in pink), dimensions marked with Σ are calculated based on those dimensions.

The translation of the physical requirements that are need for comfortable grip of a game controller and the dimensions in the CAD file were done by building mock-ups and testing different grips by multiple users (figure 24). Several factors that define the relation between the dimensions of fingers and palm to the actual physical dimensions in the CAD model were determined.

The software was tested on a random group of 20 volunteer students to check the diversity of hand geometries and how each hand creates a slightly different custom design for the controller and mouse. The measurements show significant diversity in the hand dimensions, for example, the length of the heights palm is 25% larger than the height of the shortest palm (Figure 26).
Figure 26 – comparison of two scanned hands with the same scale.

Figure 27 – The Blue mouse is generated with dimensions extracted from the biggest hand and the red mouse is from the smallest hand.
8.3: Case study 3: Changing function by folding

In this case study, two examples of foldable PCBs that change their function once folded are demonstrated.

![Image of a foldable PCB with RGB LED color change](image)

**Figure 28** - RGB LED color is changed by folding. The 2D geometry (A) can be folded to three 2D shapes (B-D), with each shape different sides are touching and closing a different circuit that light the LED in different color.

The first example is fabricated in order to test the concept of closing different circuits by connecting different pairings of magnets. A flexible PCB with a RGB LED is laminated with a rigid acrylic sheet composed of eight right angle triangles in a “Tetris”-like 2D shape configuration (see figure 27-A). Nickel plated Neodymium disc magnets are press fitted into open holes in the acrylic material and glued with conductive epoxy to traces on the PCB. This shape can be folded into 3 different 2D configurations and a single 3D shape. For each configuration a different set of edges is touching. The traces on the circuit are electrically connected to the magnets on the sides, and to the RGB LED. For each folded shape, a different circuit is closed by the contact of the magnets and this circuit lights up a different color in the LED. In this example the color of the LED changes depending on the way the PCB is folded. This is done just by leveraging the physicality of the material without using any microcontroller or software, the PCB is simply connected.
to a 6V power supply. In this case, the hardware is practically the software of the product.

The second example demonstrates the concept of products that can change their shape and electronic functionality depending on the desired task. A mouse and a game controller were selected because those products have a physical interface with the human body and the shape of such products has strong correlation to their function. Furthermore, both mouse and controller are computer accessories that are often needed to be portable and stored next to the computer or tablet when on the go. Being able to store those products flat and unifying them into one product generates significant value for users.

![Software detecting the current folding state of the mouse-controller](image)

In order for users to rapidly alternate the shape of the product, the folding process must be fairly simple. Changing the form from a mouse to a controller and unfolding into a flat state can be accomplished within 4-5 moves. The design of the shape of the PCB was created in SolidWorks using Sheet Metal tools provided by the software package. In order for the edges to touch and form a structure in both folding states a relation
between the dimensions is required. Other dimensions can be modified to affect the scale and the proportion therefore enabling customization for a particular use or user.

The first version of this example was designed to have the magnet on the edges report the current folding state of the object. Traces on the PCB were connected to an external Arduino Uno board that communicated to software written in the Processing language. The connection was made via the serial port of the computer. Connections between magnets were checked one after the other in a loop. A binary number was assigned to each connection that was checked. If the connection was “successful” the number was added to a counter. For every set of successful connections a different sum was calculated. This number was then transmitted to the computer that displays the corresponding image showing the connections that were established as well as the connections that still needs to be formulated (see figure 28).

A second version of this product was designed with actual functionalities of buttons and sensors, to illustrate how function changes in correlation to form. In the previous version the software was able to predict user intention after creating just a single fold. In the second version of the project, conductivity was checked only between four critical conductive connections that can pair in different ways for a mouse and a controller (see figure 29). It can be presumed that by making two critical connections the user will continue the folding process until completion.

This example demonstrates the object’s ability to detect its own folding state without depending on outside imaging devices. A circuit including an AtTiny 128-AU microcontroller was designed as an integral part of the product. Also located on the PCB are two LEDs and icons of a mouse and a controller. Once a critical connection is established, the appropriate LED is programmed to blink, (indicating that the user is in the processes of folding the PCB). Once the second connection is established, the LED is lit and blinking stops. On the PCB are six capacitor sensor buttons. In mouse mode, just two of the buttons are operational, for left and right click. In controller mode, all six buttons are operational; four on left (as up, down, right and left buttons) and two on
the right (for gaming tasks). In this version, an optical electronic sensor was not incorporated due to technical complexity and given that it is unnecessary for the purposes of this model, although incorporating such a device is defiantly possible.

The finished product shown in figure 30 shows the three folding states of PCB. This is an example of a user input interface that changes its form depending on the designed function. One can imagine this kind of product being used as accessory for a tablet of portable computer. The user doesn’t need to carry his peripherals with him, the PCB can be part of the cover of the tablet, the user can fold the PCB depending on the action that he would like to perform, play games with the controller or work on application that demand accurate input (that is sometime difficult to achieve with touch screen) for example working on graphic software.
Figure 31 – The three folding states of the device - flat, mouse and game controller.
8.4 Case study 4: Air mouse with curved folds

Curved folds are a special type of folds that creates two cylinder-like surfaces with different radiiuses, as appose to straight folds that create two planer surfaces. Curved fold enable creating sculptures with complex geometries and elegant appearance as can be seen in the work of Dr. David Huffman, a former professor of computer science at the University of California, Santa Cruz, and a pioneer in computational origami [64].

The purpose of the example presented here is to test the feasibility of curved folding of flexible PCBs with traces and components. An inkjet-printed PCB on a film of Polyethylene terephthalate (PET), was used as the medium for folding. In this example, an air mouse — a mouse that is operated by tilting and manipulating it in space, was fabricated.

![Flexible mouse with curves folds. The printed USB cable is torn from the main PCB (B).](image)

Curved folding with paper is possible due to the physical traits of paper that permits buckling and micro creases that can be partially soft and stiff, allowing modification in the curvature [65]. In polymer based sheets, commonly used for fabrication of flexible PCBs, such creases are not possible. These sheets can only be folded with straight folds. A technique for curved folding of flexible PCBs using perforation was used. PET material was perforated using a laser cutter by cutting it along the desired curved crease line.
using a low Pulsed Per Inch (PPI) value. This perforation creates 0.3mm holes in the material with distances of 1mm from one another. A straight fold can be established between two holes. Folding between all holes result in a series of straight fold that together create a curved crease, that is similar to a curved crease that is done if paper would have been used. Traces on the flexible PCB can pass between the holes to electrical connect the two surfaces that was generated by the fold.

The design of the mouse includes two simple curved folds that allow the user to grasp the mouse. The electronic design includes a microcontroller, an accelerometer for sensing tilts and two capacitor sensors that are printed on the PCB. In addition, the design includes a unique printed USB cable for connecting the mouse to the computer that can be torn off the main PCB. Another perforation pattern of holes in distance of 0.2mm is generated around the USB cable that allows the user to tear the cable off the PCB and connect the end to the USB socket of the computer (figure 31).

The fabricated air mouse demonstrate the feasibility of creating curved folds in flexible PCBs. Components stayed connected even after the surface of the PCB was bent as a result of the folding. In addition, the mouse is example of a product where the electronic traces and components define the visual appearance and esthetics and not hidden inside enclosures.
8.5 Case study 5: Bending PCBs - Actuated electronic paper sculptures

In this study case, the insulation material that is used for creating PCBs is thick paper in weight of 100lb. (270gr). Like all paper this material can be folded and is able to “save” its new geometry after a crease was made. However, as appose to examples shown before where folding was used to create a 3D geometry, here the ability of the paper act as a spring was leveraged. Same as a spring, paper can store mechanical energy when bent; the paper “wants” to return to its flat state, same as a spring wants to compress after being stretched. The paper is bent and its position is fixed using SMA wires. The paper keeps the wire tensioned and the wire keeps the paper from bending back. When a current runs through the wire, it shrinks, pulling the paper with it, and creating movement in the paper.

In this example, a series of 3 animated sculptures were created; caterpillar, turtle and snail. These sculptures where created as a final project for “New Textiles” class instructed by Professor Leah Buckley on the spring of 2012 at the MIT Media Lab. The goal of this project was to explore the idea of living physical and tangible interactive animation that can be fabricated using digital fabrication tools such as laser cutter and vinyl cutter and programmed using Arduino scripting language. These sculptures are composed of a single piece of thick paper that was cut using a laser cuter. Conductive traces were cut out of copper tape using a vinyl cuter and glued on the paper. A Lilipad Arduino board was integrated in each of the designs and electronic components were soldered onto the copper tape. A commercial pre-trained SMA wire product called Flexinol [64] in thickness of 0.006in was used for actuation.

In this work, the traces and components are used as visual graphic illustration on top of the sculptures. Usually, electronic components and traces are hidden from the users, and the main consideration in the layout of traces is small packaging of the product. Here, the traces are being used a graphic elements and the physical shape of component are being used as supporting decoration in the context of the form and the meaning of the sculpture.
Paper Caterpillar

The Paper Caterpillar is composed of four bent arcs that are tensioned with SMA wires. The traces on the paper are connected to a circuit board that was fabricated on a cloth in the shape of a leaf. SMAs are actuated one after the other with a small overlap in order to symbolically mimic the natural movement of a caterpillar.

![Paper Caterpillar](image)

Figure 33- Paper caterpillar

Paper Turtle

The Paper Turtle is a standalone device with microcontroller and power supply all integrated in a thin design of an iconic shape of a turtle. Each leg of the turtle is actuated separately by a Lilipad microcontroller that is attached to the turtle's back and symbolizes a turtle shell. From the Lilipad, traces follow the contour of the turtle to provide current to the SMAs in the legs and to the "eyes" LED in the head. The slow movement of the legs in response to the SMA shrinking resembles the slow movement of a turtle and enhances the metaphor of this object.
Figure 34 – Paper Turtle- Traces on the turtle are designed as graphics elements that correspond to the contour of the shape, both in top view (A) and bottom view (b).

Paper Snail

Paper Snail is an interactive piece in the iconic shape of a snail. The Paper Snail senses proximity by using capacitive sensor on its head and in response it bends. This interaction is inspired by snails’ sudden movement of their tentacles once they are touched by an unknown object like a kid’s finger. Same as tentacles, the paper snail bends with a sudden and unexpected movement and then returns slowly to its previous shape. The paper snail folds together to create its 3D shape with the Lilipad microcontroller connected to the side in a way that resembles a snail’s shell.
Figure 35 – Paper Snail – Shape memory alloy wire is tensioned between the head of the snail and the tail (C). When the snail is touched, the wire shrinks and the snail bend in a sudden movement.
9. Conclusion

The last century can be characterized as the century of mass manufacturing. The global demand for products and the growing world economy had led to the creation of mega-factories worldwide that produces millions of product every month [67]. The mass manufacturing approach is to make products cheap and fast; factories use molds that create completely identical copies of parts. Complex Products such as electronic devices are usually manufactured as assembly of parts. Each part has a single function and is typically made from a single material.

The next century is considered to be the century of digital fabrication and mass customization [67]. Unlike mass manufacturing, digital fabricated products can be customized to fit a specific user and can be fabricated on demand without the need of inventory. In addition, digital fabrication allows creating products with functional integration, similar to the structures that can be found in nature, such as vines of leafs, where materials that are used for structure are also being used to provide function. Products can be fabricated by distributing materials, in a way that generates different properties within a single material system.

In case of electronic products, digital fabrication of electronic products in a single automated process is difficult to implement, as those products are traditionally composed of two separate systems – a functional electronic material (PCB) and enclosures. In order to fabricate electronic products in one single process, the conductive and insulative materials are required to be digitally distributed while a variety of components must be integrated.

The PCB origami concept suggests an alternative approach to digital fabrication of electronic products. Products will be fabricated in 2D and then folded into 3D objects. This approach will leverage the current existing tools and processes of fabricating PCBs and thus allow creating functional products that are already embedded with electronic components and computation. As an alternative of utilizing PCB as a functional material
within the plastic enclosures, the PCB will function as the product itself, both as the outer shell and the electronic functional material.

This thesis work presents an exploration of this concept in three aspects: fabrication, design and user interaction.

The fabrication aspect was examined by creating a straightforward customization workflow of electronic products that can be applied in an online shop. Parametric CAD file was designed to accumulate different variants of the product according to the different physical dimensions of diverse users and then generate a production file for fabrication of the product. Software for extracting measurements from users’ hands was implemented and tested on a group of 20 participants. Prototypes of products for the two extreme cases in the range of scanned hands were fabricated for demonstrating the significant variation in scale and proportion between the two products.

The design aspect was researched through the creation of a new type of electronic products that can be completely flat when not in use, and can be folded once needed. This concept was implemented for computer accessories, in which the flat state is of a particular benefit as it is typically stored next to thin laptops or tablets. A specific example of a detachable iPad case that can be folded into a game controller was demonstrated.

In addition, the graphic implications of exposed traces and components were studied by creating a series of actuated sculptures and a curved folded mouse. Traces were designed not only to provide electronic current to the components, but also as a graphic illustration that relates to the design of the sculpture or the product. Moreover, the decisions of where to place the components were based in part on aesthetic arguments that related to the theme and context of the sculptures.

The user interaction aspect of the PCB origami concept was studied in the contexts of foldable surfaces with embedded information on how to fold them, in order to create an interactive folding experience. A PCB that can be folded into two 3D geometries
embedded with LEDs and conductive connections was fabricated. As opposed to prior approaches for digitally guided folding, the idea presented in this work proposes a direct approach that does not rely on external imaging or projection devices, but rather on the interaction with the material itself. This kind of interaction is much more engaging and obvious for users. In the user study conducted for this research, users performed better when guided by LEDs then when guided by a diagram and reported a joyful folding experience.

Another interaction characteristic of foldable PCB products is their ability to change their shape based on the desired task. Up until recently, most of our control over digital information was done by using tangible input devices such as mice, keyboards and buttons. The introduction of touch-screen based portable devices that function both as input (touch) and output (display), turn many of those devices unnecessary. Although interaction with touch-screen is intuitive, it does not take advantage of the human ability to manipulate and sense physical objects [47]. In addition, multi functional devices such as smart-phones and tablets usually have a rigid structure with only one form factor. As users we are expected to accept the limitation of the device and, for example, take photos in a way that is less comfortable than with a digital camera. When it comes to smart-phones, the famous saying “form follows function” does not generally apply. In “Organic User Interfaces”, d. Holman and R. Vertegaal [66] portray a vision of products and displays that are curved, flexible and can change their own shape. They vision interfaces with a form that perfectly suits the appropriate specific activity that the user is taking. They oppose the approach of an advanced Swiss army knife for electronic products where “one user interfaces fit all”.

Corresponding to this challenge, this work proposes a method of changing the shape and function of products to fit a specific task based on folding. An example of a functional 2D PCB that can be folded into a computer mouse or a game controller was demonstrated. The device can detect its own folding state and activate electronic systems accordingly.
10. Future work

Potential additional products

The research work presented in this thesis focuses on two products for demonstrating the concept of foldable electronics: a game controller and a computer mouse. Future work might extend the concept of PCB origami to other products that can be manufactured flat and folded by the user. Additional potential products include a glove embedded with IR LEDs for finger and gesture tracking systems. The glove can be customized based on the scan of the user’s hand. Another example is a universal remote controller that can operate different devices depending on the shape it is being folded into. Instead of pressing a button for choosing the affected device by the controller, the physical shape of the controller itself will change, in a way that will give a tangible representation of the changing in the function. A possible design strategy for such a device can be seen in feature 11. Another potential application is a bandage embedded with electrodes for electrotherapy. In electrotherapy, patients stick stickers with electrodes on a daily basis over a period of months in order to reduce pain. Patients need to position the stickers themselves in the same location each time, in order for the treatment to be affective. PCB origami will allow fabricating a custom-made bandage with integrated electrodes for a specific patient. The bandage will be digitally fabricated based on a 3D scan of the location that needs treatment and the desired position of the electrodes that is recommended by the doctor.

Integrated CAD software

To design foldable PCB products two types of CAD software were used. The first type is software that allows creating 3D objects and unrolling it into flat sheets that can by manufactured. The main software that was used is SolidWorks, using its sheet metal tools. The second type of software that was used is Eagle for creating electronic circuits. In Eagle, the schematic files for the circuit are designed, and based on that the PCB itself is designed by laying traces and positioning the components. The tools of this software
allow checking connections between points and verifying the circuits, based on design rules.

In the process of designing the foldable surfaces presented in this work, a back and forth approach between two software was taken. Changes in the 3D shape resulted in a change in the circuit and vise versa. This process was ineffective and time consuming. Thus, as suggested future work, new CAD software will be developed. This software will integrate capabilities of designing and unrolling 3D objects, with the design of circuit boards. Circuits design with this kind of innovative software will be flexible to changes when the overall design of shape will change. It will also be able to warn the designers if the change in shape creates a failure in the circuit. Furthermore, the software will be able to show the connections that are made in each of the folding states of the product. For example, in the PCB with RGB LED that is presented in case study 3, the software could show the closed circuit for each of the folded shapes.
11. Bibliography


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12. List of Publications


Appendix A – schematics of selective fused solder connection prototype