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Origami Diagramming

Evaluating and Improving the Origami Diagramming Tool Origrammer

Bachelor Thesis

by

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Contents

1 Abstract

The Origrammer is a desktop application for creating origami instructions, also called origami Diagrams. The goal of this program was to maximize the efficiency of creating these diagrams, as the process is slow and tedious when creating them by hand. In this paper the current state of this program was evaluated using the 10 usability heuristics by Jakob Nielsen [1] with particular focus on flaws that reduce efficiency and speed of the diagram creation. With the found flaws as a basis the Origrammer was further developed and improved.

A more flexible navigation through the folding steps with editing functions and step preview pictures was added. To further maximize efficiency, the whole system of rendering the paper was reworked as well. The Origrammer can now virtually fold paper, without the need to place every single edge or crease line by hand. Simple mountain and valley folds can be carried out and the paper folds automatically.

Various additional improvements were introduced, like folding presets for similar beginnings of an origami model, or a reworked arrow system that is more flexible and improves on several issues.

2 Introduction

Origami is the Japanese art of folding paper into models of animals, people or other objects. Folding such models can be a complex task, so in order to make origami more accessible, a system of folding instructions was developed. The diagramming system developed by Akira Yoshizawa was first published in the book *Atarashi origami geijutsu* in 1954 [2]. Yoshizawa's origami notation introduced a set of symbols and arrows to explain the different folding actions. After further development by Sam Randlett and Robert Harbin this set of origami symbols became the international standard [3] [4]. By creating these drawings for each folding step, even origami beginners could fold models. These origami diagrams (see Figure 2.1) have to be accurate representations of the paper for every folding step, in order to unambiguously explain how to fold the model. Every flap, crease and edge has to be drawn, which makes the process slow and especially error-prone for complex models. While for example the crane model in Figure 2.1 can be folded in 17 steps, more complex models can take hundreds of steps to complete.

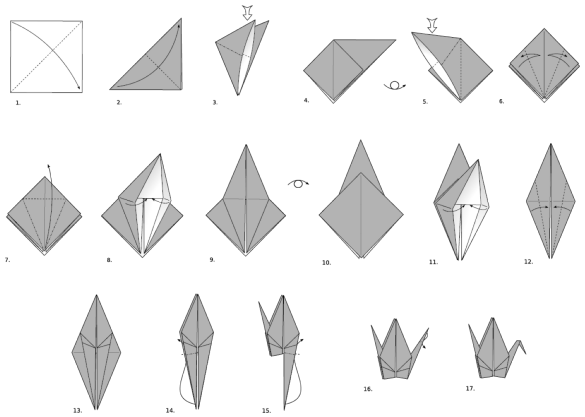


Figure 2.1: Crane Diagram - [Andrew Hudson, 2011 [5]]

In order to help artists during the creation process for origami diagrams, the Origrammer [6] was developed.

The Origrammer is a desktop application, developed by the author, which offers specific features for creating such diagrams. This program simulates, how an origami artist would create diagrams by hand. Lines, arrows, and symbols can be placed and new diagram steps can be created. Addi-

tionally, helping features are included to speed up the diagramming process as a whole. A more detailed overview and explanation of the Origrammer can be found in Section 3.

This Bachelor Thesis now aims to evaluate the current state of this program and to develop it further to improve usability, efficiency and effectivity. This thesis will start with a short summary on how the Origrammer works and what a typical workflow looks like. Afterwards, an evaluation has to be carried out, in order to get a sense of the current state of this program. Flaws and missing features have to be explicitly defined, so that a plan can be created on how to further improve the Origrammer.

As the evaluation will potentially find a multitude of different types of flaws and problems, a specific focus has to be defined. In case of this thesis, the main goal is to maximise the speed of creating origami diagrams, while also offering a usable user interface with which also novizes can work with ease. This target was set with the original plan of the Origrammer in mind:

> "*The goal for this project is to develop a desktop application that implements features specifically for the origami diagramming process. The standardized symbols and overall notations have to be included and the program* ***has to offer functions that increase the efficiency of creating diagrams***." (Hardtung, 2020, p.5 [6])

Then after evaluating and collecting potential improvements, a more detailed plan can be created on how to actually implement these changes. Although not all potential improvements can be implemented within the scope of this thesis, all found flaws should be categorized and documented, which can help further development in the future.

3 Origrammer

This section will provide a more detailed overview over the Origrammer. Its parts will be explained and a typical workflow will be shown. The Origrammer is desktop application which is being developed in Java and uses the libraries Apache Commons IO[1] and javax.vecmath[2]. Figure 3.1 shows the user interface of the Origrammer, which is split up into five major parts.

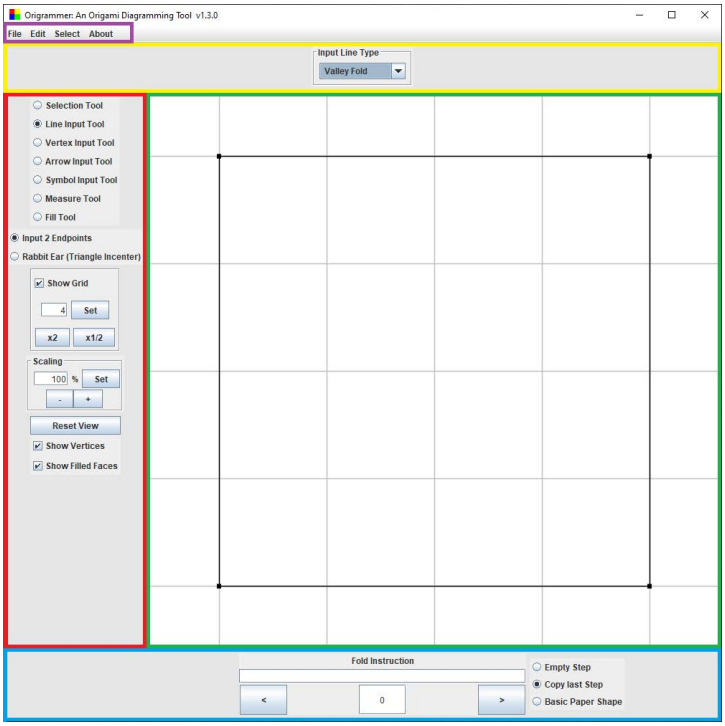


Figure 3.1: Menu Bar (Purple), Top Panel (Yellow), Side Panel (Red), Editing Panel (Green), Navigation Panel (Blue)

3.1 Menu Bar

The Menu Bar offers fast and easy access to diagram wide functions. Under `File`, the user can create a new diagram, open or save an already existing Origrammer diagram, and *export a diagram to a different format (not yet fully implemented)*. When creating a new diagram, the following panel appears, in which several settings for the diagram can be adjusted.

[1] https://commons.apache.org/proper/commons-io/
[2] https://github.com/egonw/vecmath

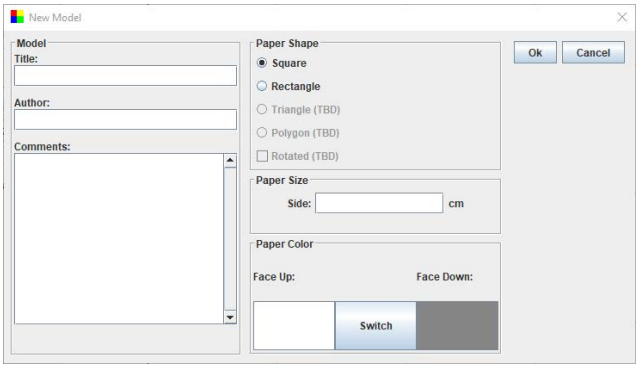


Figure 3.2: Options when creating a new diagram

The user is able to provide a `title`, an `author`, and `additional comments` (regarding copyright information, recommended paper material, or others). Additionally, paper related settings can be changed. The required paper shape can be defined (square, rectangle, triangle, polygon, or pre-rotated), a recommended paper size can be provided, and colours for both sides of the paper can be specified.

After confirming the settings for the new diagram, the paper outline of the first diagram step appears on the 3.2 Editing Panel.

The next button on the Menu Bar (`Edit`) includes the typical editing features `Undo` (Ctrl+Z), `Redo` (Ctrl+Y), `Cut` (Ctrl+X), `Copy` (Ctrl+C), `Paste` (Ctrl+V), and `Delete` selection (Delete). Additionally, the previously specified diagram information can be changed at any point under `Model Preferences` and some Origrammer-wide options can be adjusted under `Origrammer Preferences` (see Fig. 3.3).

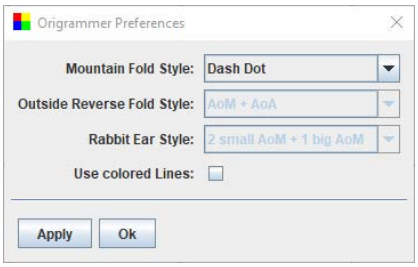


Figure 3.3: Origrammer Preferences

Lastly, under the `Select` button of the Menu Bar, the user can `Select all` (Ctrl+A) or `Unselect all` (Ctrl+Shift+A) objects on a given diagram step.

3.2 Editing Panel

The Editing Panel shows the current diagram step that is being worked on. All lines, arrows, and other symbols are being placed and edited here and all tools and input functions can then be used on the Editing Panel. Furthermore, the working grid is being displayed here, which can be adjusted on the Side Panel and offers input points for all lines, arrows, and other symbols.

3.3 Side Panel

All major input tools and adjustments of the Editing Panel are displayed on the Side Panel. The input tools consist of the `Selection Tool`, the `Line Input`, `Vertex Input`, `Arrow Input`, `Symbol Input`, `Measure Tool`, and `Fill Tool`.

Through the `Selection Tool`, the user can select, move, and edit already placed objects on a diagram step. The `Line`, `Vertex`, `Arrow`, and `Symbol Input Tools` make it possible to place the respective objects on a given step. Moreover, the user can measure the angle and length of lines within the diagram, in order to use these values as input for additional creases. The last tool is the `Filling Tool`, which offers the function to colour parts of the paper, according to the specified paper colour.

Furthermore, the options for the assisting grid of the Editing Panel can be changed, the scaling can be adjusted to see more detailed parts of a diagram step, and the rendering for vertices and the coloured faces of the diagram can be turned off.

3.4 Top Panel

After choosing a tool from the Side Panel, the respective input/editing options of the activated tool are being displayed on the Top Panel. These can be for example sliders for rotations, check boxes for mirroring a symbol, combo boxes for choosing different line/arrow types, and other things.

3.5 Navigation Panel

The Navigation Panel makes it possible to move through the individual diagram steps, as well as to create new ones. When creating a new step,

the user has three different options. The new step can either be completely empty, only consist of the original paper outlines, or can be a full copy of the previous step.

This is also the area, where the user can write down the textual folding instructions for a given step.

4 Evaluating Origrammer

This evaluation of the Origrammer is supposed to give a basic feedback on which parts of the Origrammer are most problematic and could benefit from automating parts of their processes. The main metrics of the evaluation will be efficiency or speed of use, which can be measured and systematically determined. Consequently, user involvement in the evaluation is at this stage of development not hugely impactful and therefore not used here. Nonetheless, an evaluation with real users should be carried out at a later time before final release of the program, as even though the time spend for certain processes will be reduced during this work, some usability issues can still be overlooked.

As a result of the aforementioned reasons, the evaluation will be carried out using the *10 usability heuristics* by Jakob Nielsen [1]. These heuristics offer clear reference points to accurately evaluate the Origrammer. Though this apporach also brings limitations, as is mentioned by Nielsen and Molich in the proceedings of the SIGCHI Conference on Human Factors in Computing Systems from 1990.

> "*A disadvantage of the method is that it sometimes identifies usability problems without providing direct suggestions for how to solve them.*"
> (Nielsen and Molich, 1990, p. 255 [7])

This limitation of not providing direct solutions for the found flaws is why this chapter will focus on finding problems and shortcomings of the Origrammer first. Afterwards, solutions can be developed that optimally fix most, or all, discovered issues without contradicting or counteracting other measures. These solutions should prioritize efficiency, which gives a clear metric on which one of multiple changes should be implemented.

As there won't be user involvement for this evaluation process, other measures have to be taken to ensure maximum efficiency and thoroughness. This is why the following section shows an exhaustive list of all parts and features of the Origrammer. Figure 3.1 roughly displays what features are located where on the Origrammer.

4.1 Origrammer Feature List

1. **Menu Bar (Purple)**
   (a) New File (b) Open File (c) Save File
   (d) Export File (e) Model Preferences (f) Origrammer Preferences
2. **Side Bar (Red)**
   (a) Selection Tool
      1. Click to Select 2. Hover over Object 3. Rectangular Selection
   (b) Line Input
      1. Two Point Input 2. Triangle Incenter
   (c) Vertex Input
      1. Absolute Position 2. Fraction of a Line
   (d) Arrow Input
      1. Valley Fold 2. Mountain Fold 3. Turn over
      4. Push Here 5. Pull out 6. Inflate here
   (e) Symbol Input
      1. Leader 2. Repetition Box 3. Next View Here
      4. Rotations 5. Hold Here 6. Hold Here and Pull
      7. X-Ray Circle *8. Fold Over & Over* 9. Equal Distances
      10. Equal Angles 11. Crimps 12. Pleats
      13. Closed Sinks
   (f) Measure Tool
      1. Measure Length 2. Measure Angle
   (g) Fill Tool
   (h) Grid Settings
   (i) Scaling Settings
3. **Navigation Panel (Blue)**
   1. Fold Instructions 2. Step Navigation 3. New Step Options
4. **Top Panel (Yellow)**
   See Side Panel for related features, as options for the selected Side Panel Tools appear on the Top Panel.
5. **Editing Panel (Green)**
   See Side Panel for related features, as the selected Side Panel Tools are being used on the Editing Panel.

4.2 10 Usability Heuristics

With the Origrammer Feature List as a basis, the evalutation using the 10 Usability Heuristics can be carried out. Every feature from the list will be checked against all 10 heuristics in order to try and maximise the completeness of the result. The found usability issues will then lead to the planning of potential usability improvements. Additional focus should be set on the 7th heuristic *Flexibility and Efficiency of Use*, as it includes the main goal of improving the efficiency of creating diagrams with the Origrammer.

1. Visibility of System Status

Nr:	Affects	Impact	Description
1.01	2.b; 2.d-2.g	3	When an action requires multiple input points (e.g. placing a Fold Line by two endpoints), the user doesn't know where he is in the process.
1.02	2.d; 2.e	7	Always show a preview of the `OriArrow` or `OriSymbol` before final placing
1.03	3.2; 3.3	6	The user doesn't know how many diagram steps there are overall and where they are

2. Aesthetic and Minimalist Design

Nr:	Affects	Impact	Description
2.01	2.a-2.i	4	The text in the Tool Selection on the Side Panel should be replaced by icons
2.02	4	3	The text in the TopPanel for input and editing options should be replaced by icons
2.03	2.f; 3	6	The User Interface should always fit properly (is currently not fitting in the SidePanel for MeasureTool & for some settings in the TopPanel)

3. User Control and Freedom

Nr:	Affects	Impact	Description
3.01	2.a; 2.b; 2.d; 2.e; 2.g	5	User should always be able to cancel an action (e.g. when inputting an object with multiple input points))
3.02	3.2; 3.3	8	Navigating through the diagram steps is unflexible and slow
3.03	2; 3; 4; 5;	10	Creating the individual diagram steps is slow due to the need of placing lines one by one

4. Consistency and Standards

Nr:	Affects	Impact	Description
4.01	2.a; 2.b; 2.d; 2.e; 2.g	2	Editing options on the TopPanel should be labeled correctly (consistent naming scheme needed)
4.02	2.a; 4; 5	6	When selecting and editing Symbols/Arrows make it consistent (e.g. when selecting different OriObject types like OriArrows and OriSymbols at the same time, the TopPanel overfills)
4.03	1; 2; 3; 4	6	UI elements should have consistent sizes (e.g. "Set" Buttons, `JTextFields`)
4.04	1; 2; 3; 4	4	The sequential placement of UI parts should be consistent (e.g. for Input and Editing options on the TopPanel, have `JTextFields` first and then `JCheckBoxes` to the right

5. Error Prevention

Nr:	Affects	Impact	Description
5.01	2.b.2	7	Selecting the same point multiple times breaks the RabbitEar lines
5.02	2.e.10	8	Selecting points in the wrong order breaks inputs for the EqualAngle symbol
5.03	2.g	7	Selecting the same point multiple times breaks the FillTool
5.04	1.a; 1.e;	6	Restrict the input of every JTextField (e.g. only allow numbers for number inputs)

6. Recognition Rather than Recall

Nr:	Affects	Impact	Description
6.01	2.f	5	User should not be forced to remember the measured values (currently the measured values are being hidden, once the user selects a different tool from the SideBar)

7. Flexibility and Efficiency of Use

Nr:	Affects	Impact	Description
7.01	2.h	3	Give shortcuts for the Grid halve/ double buttons
7.02	2.i	3	Give shortcuts for the ResetView button
7.03	2.i	3	Give shortcuts for the step by step zoom-in/zoom-out
7.04	2.b	8	Give more Line Input options to avoid tedious work with grid adjustments
7.05	2.d; 3; 4	8	Give more flexibility when editing or placing arrows
7.06	2.e; 3; 4	8	Give more flexibility when editing or placing symbols
7.07	3.2; 3.3	9	The user can not change the order of steps, remove unwanted steps, or enter new steps between existing ones
7.08	2.g	7	The user has to select the vertices by hand and is limited to triangles
7.09	5	6	The user has to repeat similar diagram beginning steps for every new diagram
7.10	2; 3; 4; 5	10	Creating the individual diagram steps is slow, because lines have to be placed seperately
7.11	5	10	The diagramming rule of distorting the model in order to see hidden layers (Lang, 2011, para. *Distort the model for clarity* [8]) is unflexible when having to change every single line by hand

8. Recognition, Diagnosis and Recovery from Errors

Nr:	Affects	Impact	Description
8.01	2.b-2.	5	Error messages for wrong user inputs should be self-explanatory
8.02	2.b-2.g	4	Error messages for wrong user inputs should explain how to fix the error

9. Help and Documentation

Nr:	Affects	Impact	Description
9.01	2.a-2.i; 3; 4	6	Show tooltips for all icons or non self-explanatory parts
9.02	2.a-2.g	7	Show short explanation on how inputs work for every possible input feature (could be combined with Nr.01 –> 4.2 Visibility

10. Match between System and Real World

Nr:	Affects	Impact	Description
10.01	2.b-2.e	5	Use “Origami terminology” everywhere (e.g. Rabbit Ear instead of Triangle Incenter; Next View Here Symbol instead of Eye Symbol)

5 Changes and new Features

This section will build on the discovered usability issues found during the initial evaluation process (see Section 4). On this basis, solutions can be developed that fix the most impactful usability issues. Furthermore, new features can be created that increase productivity (by automating processes and part of the workflow), while also fixing the current problems.

5.1 Graphical User Interface related changes

These changes include everything that is related to the graphical user interface that the user interacts with.

5.1.1 Overall UI Changes

Every feature area (e.g. grid options, scaling options, arrow/symbol inputs etc.) should be seperated through a `EtchedBorder` with its name as the title. Within these borders, elements should follow a consistent order. This is why this hierarchy is being set for the placement within these areas: `JRadioButton, JTextField, JButton, JCheckBox`.

Though additional `JLabels` can be used to explain or to give indicators what the elements do specifically. Whenever possible, icons should replace text and tooltips should be used to give further explanation. Explanatory `JLabels` should only be used when icons and tooltips are not enough.

Additionally, to the more consistent placement of elements within the UI, their sizes should be standardized as well. `JTextFields` for example should only be large enough to encapsulate the largest possible entry. This means that the `height` should always be set to 25 pixels (and the `width` depending on what is being entered (e.g. entering an angle between 0-360° will be shorter than entering the textual explanation of a folding step).
Fixes: #2.01; #2.02; #2.03; #4.01; #4.03

5.1.2 Side Panel

The text of the `JRadioButtons` at the tool bar should be replaced by self-explanatory icons in order to improve overall clarity. But the textual explanation of all the tools should still be present to help especially novizes. This

can be done through tooltips that appear when hovering over the buttons.
Fixes: #2.01; *#2.03*

At a later point a complete redesign and rework of the UI will have to be carried out, in order to facilitate the goal of a unified and obstructionless design. At the current stage of development though the focus is being set to increase the efficiency and speed of creating origami diagrams.

5.2 User Input related Changes

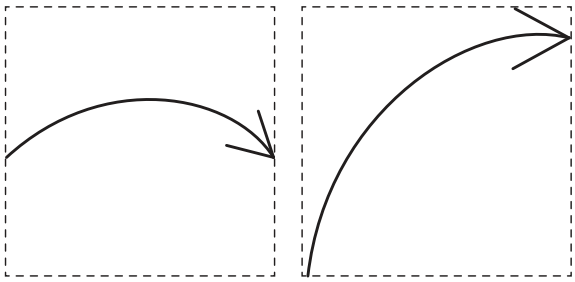
5.2.1 Arrows & Symbols

A large part of the Origrammer is made up of the different arrows and symbols that can be used in diagrams. So far, these objects were simple vector graphics that were being placed on the diagram as `ImageIcons` of `JLabels`. This approach did initially work, but brought restrictions and problems with it.

As vector graphics do not have explicit width or height values, the library Batik[3], which was being used to load the .svg files, presented wrong values to the `JLabel.setBounds(width, height)`-method. As a result of this limitation, the arrows & symbols got partially cut off at the original bounds of the `JLabel` when rotating them. To fix this issue, a new, pre-rotated vector graphic was being loaded whenever an arrow or symbol got rotated. Though this in turn facilitated itself in a wrong, always square border around the arrows and symbols. Additionally, this made interactions with arrows and symbols far slower and unflexible.
Another sideeffect was a change in scale when rotating a non square object. A `JLabel` tries to display the biggest possible object that can fit within the border bounds. As seen on Figure 5.1 the size of the arrow changes after rotating it by 45°.

As a result of these problems and limitations, the decision was made to completely rework how arrows & symbols function in the Origrammer. The new approach was to rebuild all objects with simple `java.awt.Shape`-objects. This gave total control over rotations, scaling, and on-the-fly-editing of all arrows/symbols. Another advantage was the removed reliance on `JLabels` and associated with that, there were no longer issues with wrong

[3] https://xmlgraphics.apache.org/batik/



(a) Straight Arrow (b) Angled Arrow

Figure 5.1: Unwanted Scaling when Rotating
The wrong, always square hitbox, regardless of arrow shape

hitboxes or different scaling while rotating. The only disadvantage was the work-intensive nature of remodeling all arrows and symbols with `Shape`-objects by hand.

Fixes: #1.02; #7.05; #7.06

5.2.2 Filling Tool

The current limitations of the Filling Tool make it slow and cumbersome to use. The user has to manually input three vertices in order to create a triangle that shows the specified filling color. The limit of only three vertices per `OriFace`-object was originally introduced to give finer control for the user, as well as simplifying the development process for this feature.

But this decision went against the original goal of minimizing the time needed to create diagrams. As a result the Filling Tool has to be reworked, so that it can be used faster and with less user inputs.

The new Filling Tool only requires one mouse click to fill an area with colour. When clicking in an area, the Origrammer first looks for the closest line to the `clickPoint`. Afterwards, both endpoints of the line are being checked for other touching or intersecting lines. The additional lines that were found have to be checked if they are visible from the original `clickPoint`, which would mean, that they are part of the enclosing lines. The endpoints of every new discovered line will be checked the same way, until a full enclosure of lines is established. Once this has happened, a `GeneralPath` is created that, goes through all points of the enclosing area. Lastly, the area of the `GeneralPath` can be filled with the specified colour.

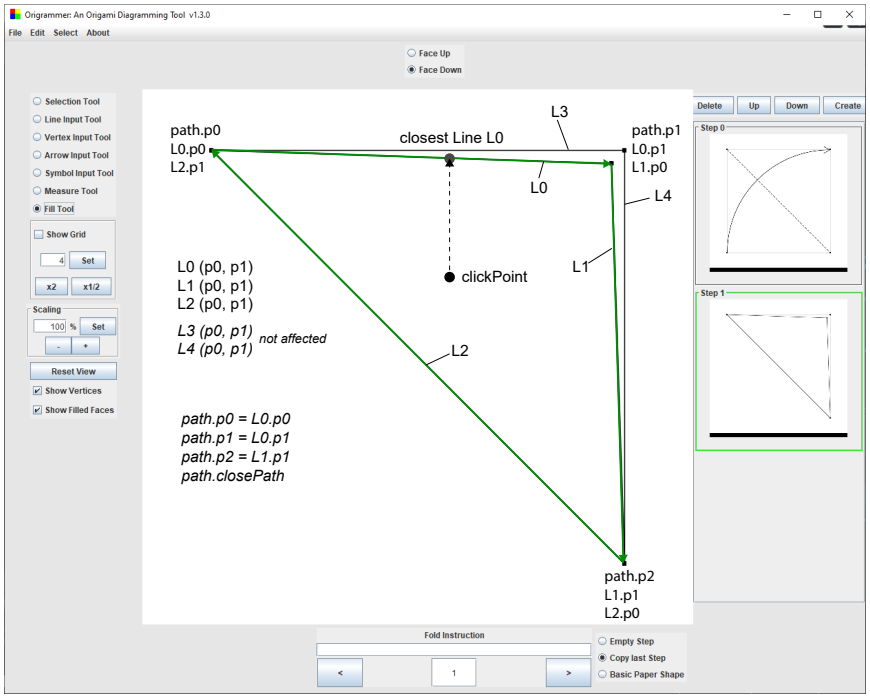


Figure 5.2: Example on how the Filling Tool works after the rework

5.3 New Origrammer features

These new features should increase the productivity and efficiency of the Origrammer. The focus should be set on maximising the work that can be done in the shortest amount of time. This will be achieved by implementing features that either automate parts of the workflow, or that give new, faster possibilities of achieving the goal.

5.3.1 Step Navigation & Step Editing Options

Currently, the Origrammer can create new diagram steps with three different options (*Empty Step*, *Copy last Step*, and *Basic Paper Shape*). Furthermore, the user can navigate through them with a *Next-Step-*/ and a *Previous-Step-*button. Though this approach brings limitation with it. Moving through the steps one by one hinders the overall usefulness and especially the speed of working with the Origrammer.

Deleting redundant steps can be quite important once the folding sequence goes through changes or simply when the user has made a mistake. In the same sense of offering solutions to user made mistakes, the Origram-

mer should make it possible to move steps to a different position within the diagram. Being able to create new steps in between existing ones can also be quite useful in negating user error.

An additional problem arises, once a diagram with a lot of steps (100+) is created. As the user currently only knows where he is in the folding sequence by the step number, this can lead to confusion. For example when folding an animal, there can be a different folding sequence, depending on what the artist decides to fold first (e.g. head first, the front or the hind legs, the tail, the abdomen, or the back). In order to continuously see where the user is within the diagram, there should be a small preview picture for all the steps within the step navigation. This will give the user an idea on what area a range of steps is working on. When clicking on one of the previews, the clicked step should made active and should be displayed on the Editing Panel.

As a result of the mentioned issues, the step navigation will be reworked to offer more functionality, visibility and ease of use. This will be accomplished by offering the following features in the rework:

1. Small preview picture of a step
2. Click on preview picture to show the step in the Editing Panel
3. Show step number, the preview picture, as well as the folding description of the step in the navigation
4. Delete a selected step
5. Move a selected step to the front or the back
6. Create a new step between existing steps

Fixes: #1.03; #3.02; #7.07

5.3.2 Folding Presets

In origami diagramming, there are eight widely established bases (Lang, 2012, p.53-64 [9]). When starting with these bases, one can fold a variety of different models. The bases in question are:

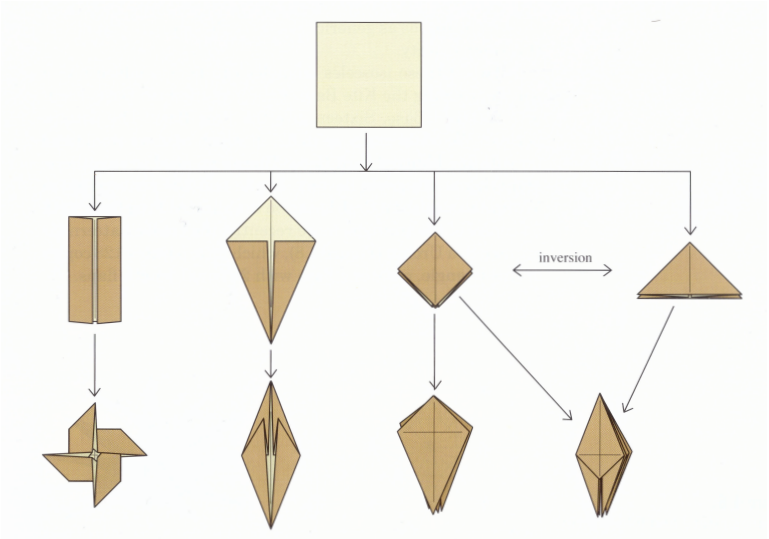


Figure 5.3: Family Tree of the standard bases.
Top to bottom and left to right: Cupboard Base, Windmill Base, Kite Base, Fish Base, Preliminary Fold, Bird Base, Waterbomb Base, Frog Base - (Robert J. Lang, 2011, p.61 [10])

As these bases serve as the starting point for a wide array of models, it would be helpful to include them in the Origrammer. By giving the user the option to start a diagram with one of these bases, the overall diagramming process will be shortened by quite a bit. Not having to keep repeating the same beginning steps for different models will save time and can also show beginners of the program, how parts of the Origrammer look like or work.

Additionally to the origami bases, instructions on how to fold different grid sizes, should be included in the folding presets as well. Folding a 3x3, 5x5, or 7x7 grid from a square paper is not as straight forward and requires multiple folding steps to achieve.

Fixes: #7.09

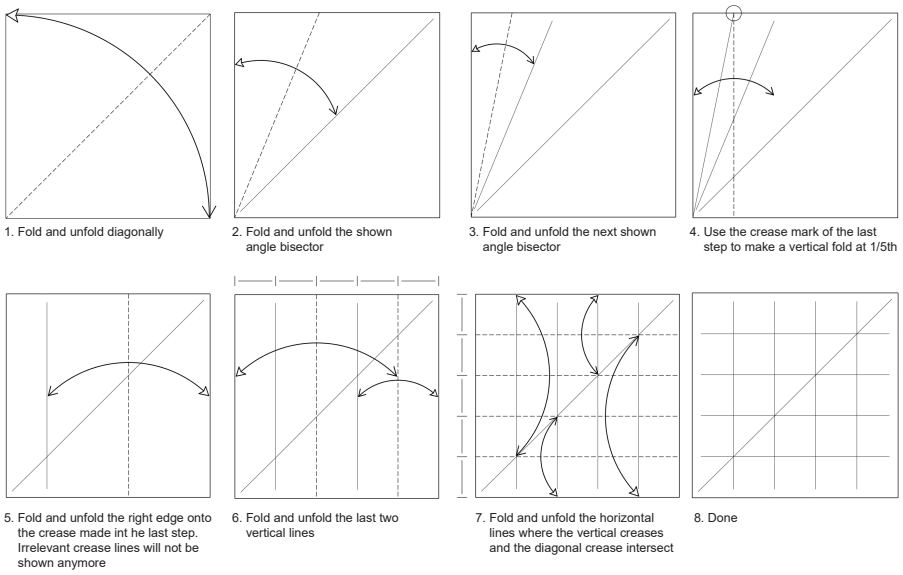


Figure 5.4: Example diagram of a 5x5 grid made with the Origrammer

6 Virtual Folding of the Paper

When creating diagrams with the Origrammer, the most time consuming activity is the placement of all required lines. All edges, current creases and existing creases have to be placed precicely, in order to allow the folder to closely follow the instructions simply by the visual cues. This large bottleneck in the diagramming process can only be eliminated by simulating the actual folding process virtually.

Being able to drag and drop a corner or edge of the paper to the desired position would reduce the work required by a large amount.

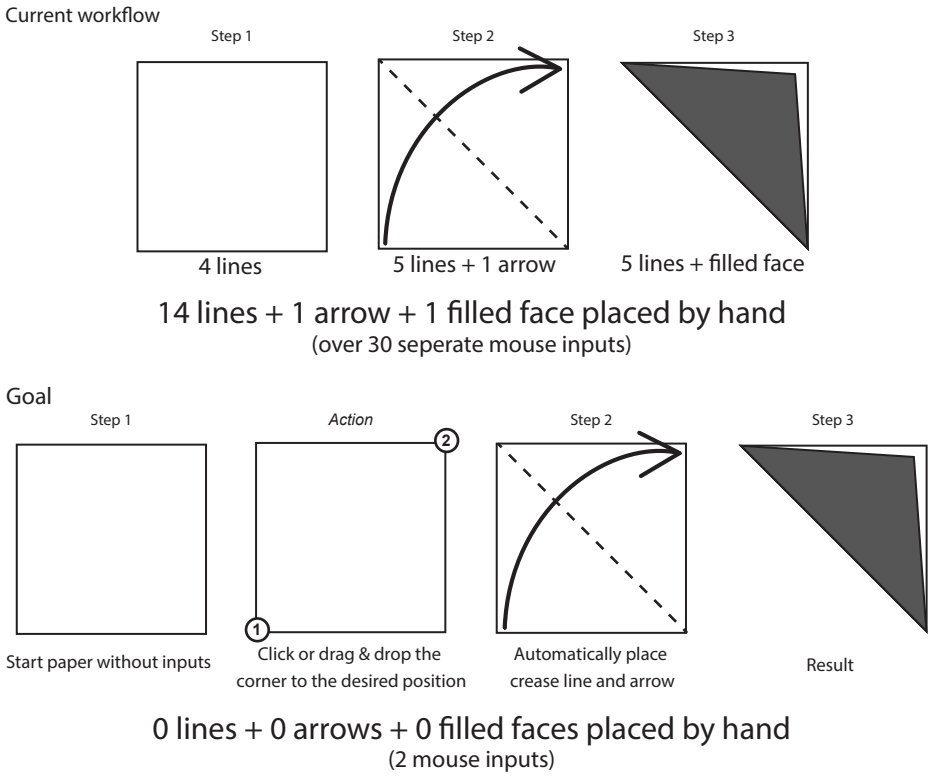


Figure 6.1: Current workflow (top) & Desired workflow (bottom)

In order to implement this automated folding, several parts of the Origrammer will have to be reworked. As there have already been a few attempts at simulating paper folding, the following sections will explore these projects in order to gain additional knowledge relevant for the Origrammer rework.

6.1 Related Works

Folding virtually to simulate folding origami models is a goal that has been pursued by several projects. This section will list and explore several of those attempts in order to possible gain information on how the folding had been implemented in these projects. Then with that knowledge the implementation for the Origrammer can be developed while improving on the previous attempts.

6.1.1 Origami Simulation

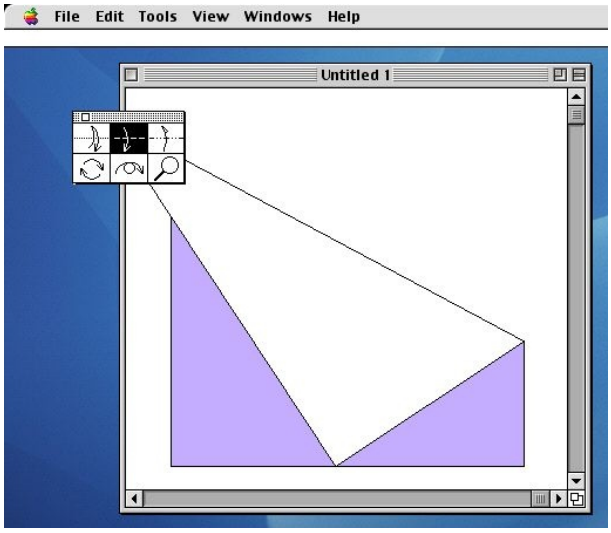


Figure 6.2: Origami Simulation by Robert J. Lang

One of the first documented approaches to simulate origami folding is *Origami Simulation* [11] by Robert J. Lang. This desktop application was "written in Object Pascal for the Mac OS, using Lightspeed's THINK Pascal and the THINK Class Library" (Lang, 2015, para. 2 [11]) . It was able to carry out simple Valley and Mountain Folds, as well as to rotate and turn the paper around. Though as this application was originally developed in the 1980s, it is now only runnable on Mac Classic mode, which means it will no longer work on Mac OS X 10.5 and later or on Intel-based Macs. However the source code is still publicly available[4] and could prove useful for conceptional purposes when implementing the virtual folding for the Origrammer.

[4] http://www.langorigami.com/wp-content/uploads/2015/09/origamisim.src_.zip

6.1.2 Foldinator

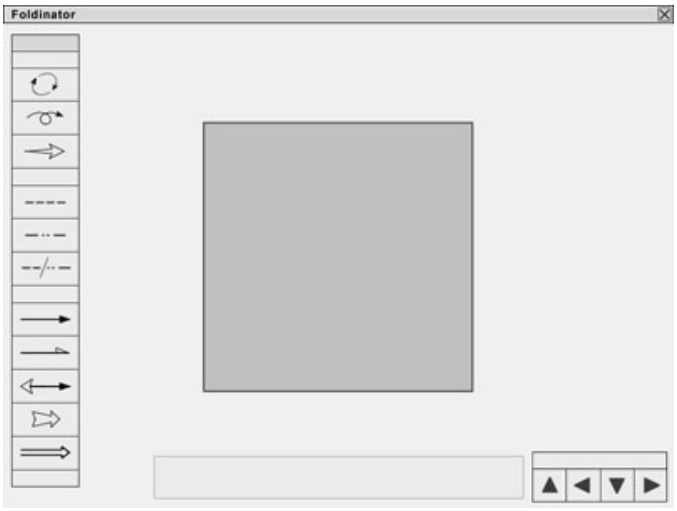


Figure 6.3: Foldinator by John Szinger

The Foldinator [12] is a software application developed by John Szinger with the goal of virtualizing the folding process and subsequently creating origami diagrams with it. The program was originally developed in Flash using ActionScript1 but was later ported over to the Apache Flex SDK[5]. The paper in Szingers approach was represented by polygons that got split up and moved when folding. Further than that there is no puplicly available explanation on what constraints and processes are used for the folding itself.

Featurewise, the Foldinator was able to carry out Valley and Mountain folds, rotate, and turn the paper around.

[5] http://flex.apache.org/index.html

6.1.3 eGami

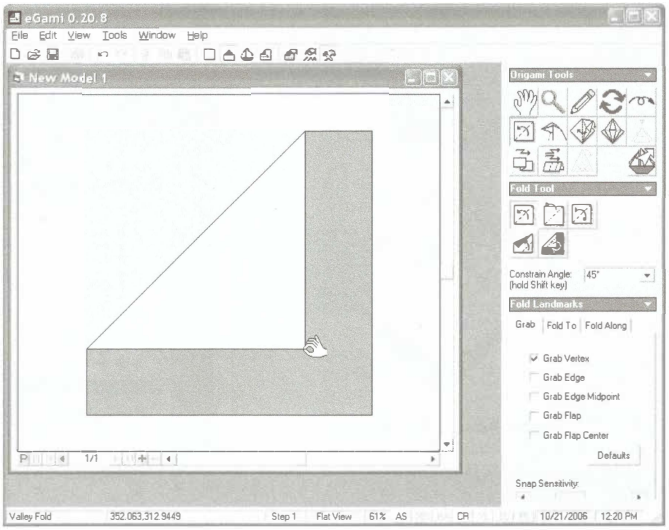


Figure 6.4: eGami by Jack Fastag

The computer software application eGami [13] by Jack Fastag can simulate the folding of flat origami models and create automatically generated diagrams. While there doesn't seem to be any publicly available information on which programming language the application was developed on, the paper published in *Origami⁴: Fourth International Meeting of Origami Science, Mathematics, and Education* contains more detailed explanations of the inner workings.

eGami is using a winged-edge boundary representation (Foley, 1996, p.545-546 [14]) to store and work with a polygon mesh, which is representing the paper. Through this representation, a series of constraints ensures correct properties of the paper. Additional constraints also guarantee that only valid folds can be carried out:

"

(a) *All polygons are closed*

(b) *All edges are used by not more than two polygons*

(c) *Each vertex is referenced by at least two edges and at least one polygon*

(d) *The mesh is completely connected, topologically planar and has no holes*

(e) *Vertices on the raw edge of the paper must be connected to exactly two "raw" edges*

(f) *Vertices inside the paper must satisfy Maekawa's Theorem*

(g) *Paper does not stretch, which means vertex positions are fixed and edge lengths are constant*

(h) *Paper faces are flat, which means that each polygon's vertices are coplanaer and implies that only rigid folds are allowed*

(i) *No rips or holes*

(j) *Paper is infinitely thin, implying that paper "creep" is not taken into account*

(k) *Only flat folds are allowed, meaning each vertex inside the paper must satisfy Kawasaki's Theorem*

(l) *Paper does not intersect itself*

"(Fastag, 2006, 3.1 [13])
Implementation of Maekawa's and Kawasaki's theorems of flat foldability[15] in addition to the other mentioned constraints could improve the reliability of Origrammer's virtual folding and should be pursued further.

6.1.4 Conclusion

Previous attempts at virtually folding paper for diagram creation have proven its viability but also either haven't been updated in years or never proceeded further than simple Valley and Mountain folds. Additionally, for most projects there is no detailed information available on how these programs work and how they actually implement the folding simulations. So for the Origrammer, all underlying processes should be explained and documented. This will give a starting point for any other future approaches to the virtual folding. Furthermore, a set of constraints (similar to eGami 6.1.3) should be implemented that ensure only valid folds can be made.

6.2 Requirements

The following aspects build the concrete requirements of what the virtual folding should do automatically and what has to be kept track of in order to implement this system of simulated folding.

The paper lines have to be stored in a way where their relations and connections to each other are stored and preserved. Then, as seen in Figure 6.1, the folding arrows have to be placed automatically when folding parts of the paper. The folding line where the new crease is created should be placed automatically as well. This crease line might also have to go through multiple layers of paper, which will have to be checked against for each folding action. Lastly, the folded part of the paper has to actually change position and direction, and possibly show the differently colored side of the paper.

6.3 Current Status

So far, every line got stored within a single `ArrayList<OriLine>` and was otherwise completely independent of the other lines. An additional `ArrayList<OriVertex>` was kept track of, in order to efficiently iterate through all vertices that can be used as an input point for new lines, arrows or symbols. All arrows and symbols got also stored within their respective `ArrayList<>` per folding step. Lastly, the folding steps themselves got stored within an `ArrayList<Step>` as well, which made saving the full diagram in a .xml-file simple and efficient.

This approach worked while there were no dependencies between the lines and vertices. But when folding virtually, several dependencies and other values have to be kept track of. These include among others the edge lines, existing creases, newly made creases (all with their specific line types), correct layering when rendering folded paper, correct colouring of different paper sides, and the rendering with slight distortions to show hidden layers/flaps (Lang, 2011, para. *Distort the model to show all the layers* [8]).

6.4 Reworked System

The new implementation works by splitting the actual paper model into `OriPolygons` that can be folded, split up, and rendered (see Listing 1).

Listing 1: OriPolygon

```
OriPolygon {
        OriVertexList vertexList;
        ArrayList<OriLine> lines;
        int height; /*height of the polygon (rendering order)*/
}
```

Once the user inputs a new fold line, the Origrammer checks which `OriPolygons` are affected by the fold and subsequently splits them at the points where the folding line crosses the edges of a given polygon. The resulting line at the newly created crease is now a shared line between the two smaller, split up polygons. This is more closely visualized at Figure 6.5.

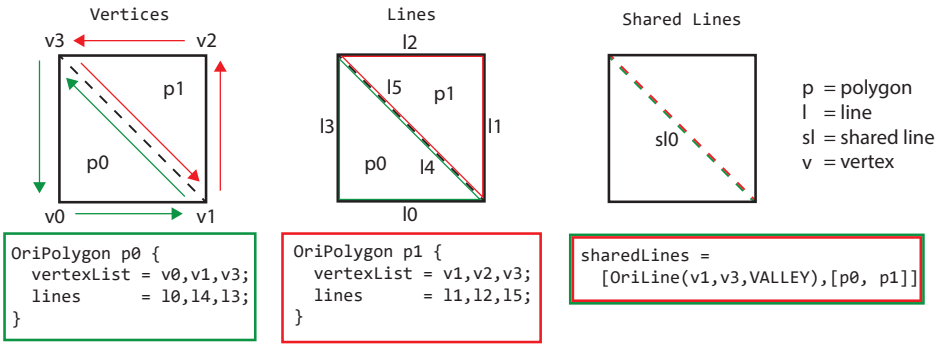


Figure 6.5: Reworked Paper Representation through `OriPolygons` and `sharedLines`

Every `OriPolygon` in turn consists of a `OriVertexList`, which contains all vertices of said polygon in a counter-clockwise order. Additionally, an `ArrayList<OriLine>` is required to keep track of the edge lines of the paper. As an `OriLine` also includes the line type, the lines within the `OriPolygon.lines`-list can have the type `EDGE` or `SHARED`.

For the case when a polygon is sharing a ling with another polygon, the `HashMap<OriLine, ArrayList<OriPolygon» sharedLines` was added.

Listing 2: New Implementation of Paper Model

```
ArrayList<OriPolygon> polygons

HashMap<OriLine , <ArrayList<OriPolygon>> sharedLines
```

This *shared lines*-list contains all the shared lines in combination of which polygons are sharing the given line. Additionally, the real line type is stored

here, which is later used for rendering. If the `OriPolygons` would store the actual line type instead of the mockup type `SHARED`, then there would be no programmable connection between several `OriPolygons`. This would make folding lines that go through multiple polygons at the same time harder to calculate and progress from.

Alternatively, there could be a flag for each `OriLine` that would signalize if it also is a shared line. But then one would have to iterate through all `OriPolygons` and check every line in them when looking for the connected polygon of a given shared line. So even though the `HashMap` of shared lines has to be updated and kept track of at all times, it is still more flexible and efficient compared to the system of flagging an `OriLine` as a shared line.

Listing 3: OriVertexList, OriVertex, and OriLine

```
OriVertexList {
        int n; /*vertex count*/
        OriVertex head;
}

OriVertex {
        Vector2d p; /*Vector2d(x, y)*/
        OriVertex prev;
        OriVertex next;
}

OriLine {
        OriVertex p0;
        OriVertex p1;
        int type;
        /*NONE, EDGE, MOUNTAIN, VALLEY, XRAY, CREASE,
        (SHARED), (DIAGONAL)*/
}
```

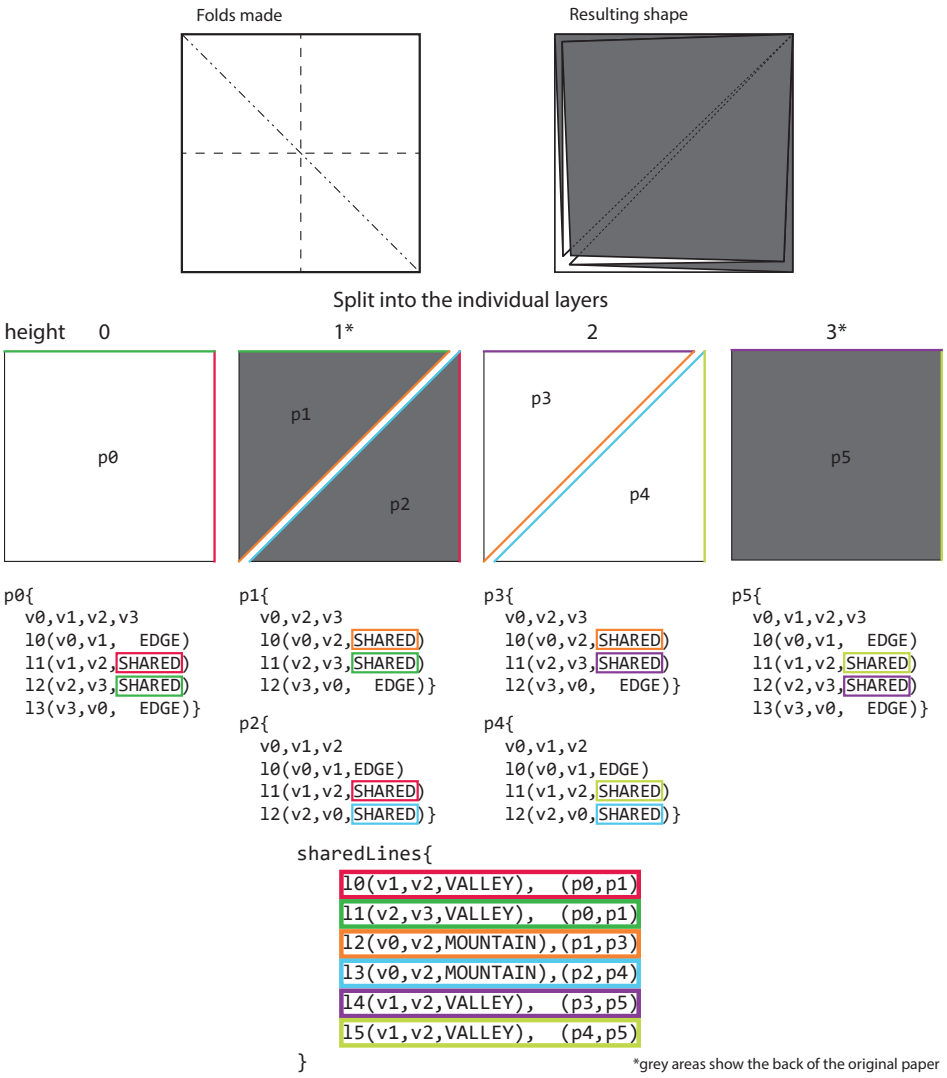


Figure 6.6: A more complex example of splitting polygons and multiple layers

The example in Figure 6.6 shows a slightly more complex example, on how the Origrammer splits the polygons and creates the correct shared lines. Additionally, in this case multiple layers of the paper have to be rendererd and kept track of. This height value is only preserved for each `OriPolygon` and is not used in the vertices, lines, or shared lines. It can be seen that for each shared line there can only be two `OriPolygon`s that share one edge. So when making a fold on one polygon and said fold crosses a shared line of this polygon, the Origrammer only has to search for the counterpart polygon,

that shares the same line. This process can be seen in Figure 6.7, where a fold through multiple layers is carried out. Internally, the Origrammer starts with a simple folding line on the top polygon that goes to its edges. If one or both endpoints of the folding line end in a shared line, it is clear that other polygons are also affected by this fold. Then one only has to iterate through the list of shared lines and find the connected polygon/s. Once the new `OriPolygon`/s have been found, the same process can then be repeated.

1. Create the folding line on the top layer
2. Check both endpoints if they are ending in a shared line
3. Find the connected polygons on the sides that have a shared line
4. Repeat until on layer 0 or no other polygons are found

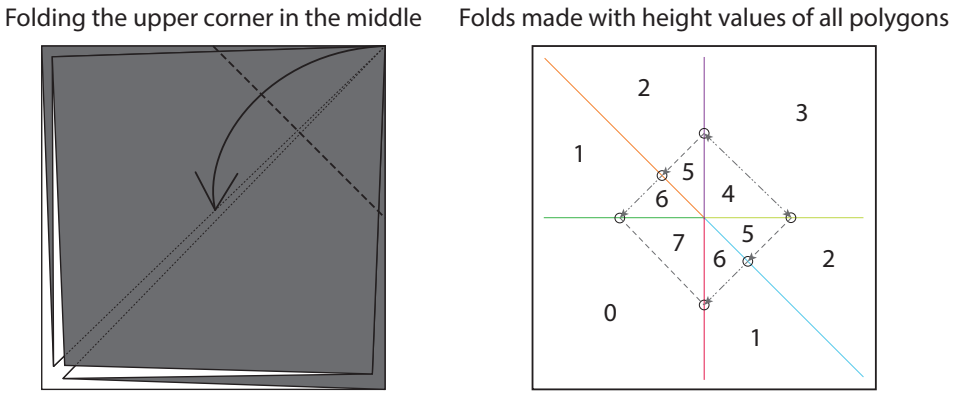


Figure 6.7: The process of folding through multiple layers and the updated height values

On Figure 6.7 it can also be seen that the colored lines (shared lines) will have to be splilt up when applying the fold. The marked crease lines also represent newly made shared lines, as they split existing polygons.

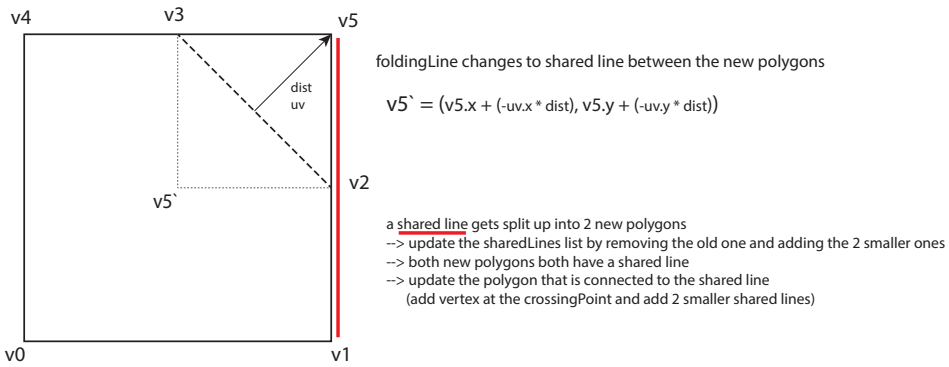


Figure 6.8: Process of updating the new vertex positions after folding and splitting existing shared lines

6.4.1 Current Limitations

The current implementation of the virtual folding still brings limitations with it. While the use can freely fold the paper, even through multiple layers and in different directions, several more complex folding procedures can not be carried out.

Open and closed sinks, reverse folds, crimps and pleats,

7 Problems & other Findings

This section discusses decisions and problems during the development process.

8 Prospect

The automation of processes in the Origrammer has changed the workflow of creating diagrams as a whole. Instead of placing lines, arrows, and symbols one by one, the user can simply fold the paper with two mouse clicks and the paper is folded automatically. Furthermore, the correct folding arrow is placed without any additional user input and the following step is started automatically.

With the use of the step navigation, the user can navigate more efficiently and flexible. Steps can be moved, duplicated, deleted and created freely and the preview images of said steps shows the user where he is in the diagram.

Further development in the future could improve on the virtual folding, especially for more complex folding actions like rabbit ears, crimps and pleats, reverse folds, and opened/mixed/closed sinks. Another flaw of the current folding system is the inability to display curves and 3d-shaped parts of the origami model. This would be especially important during the shaping process at the end of folding a model.

The user interface is also not final in multiple parts of the Origrammer.

Glossary

Diagram Origami diagrams give folding instructions for origami models. They usually consist of a representation of the model per folding step, the folding instruction in symbol form, as well as the folding instruction in text form. 4

Origami (jpn: *ori* = *folding* and *kami* = *paper*) is the art of folding paper into models of animals, people or other objects. 5

Origrammer Origrammer is the name of the diagramming program developed within the scope of this project. 4, 5

List of Figures

References

[1] Jakob Nielsen. 10 usability heuristics for user interface design, April 1994. https://www.nngroup.com/articles/ten-usability-heuristics/ [Online; accessed June 10, 2020].

[2] Akira Yoshizawa. *Atarashi origami geijutsu*. Origami Geijutsu-Sha, Tokyo, 1954. no ISBN.

[3] Joseph Wu. Origami: A brief history of the ancient art of paperfolding, 2006. http://www.origami.as/Info/history.php [Online; accessed Juli 08, 2020.

[4] Koshiro Hatori. K's origami: History of origami. https://origami.ousaan.com/library/historye.html [Online; accessed Juli 08, 2020.

[5] Anrew Hudson. Crane, 2011. https://ahudsonorigami.files.wordpress.com/2011/11/tsuru.pdf [Online; accessed March 21, 2020].

[6] Julian Hardtung. Origami diagramming: Development of a desktop application for creating origami diagrams, April 2020.

[7] Jakob Nielsen and Rolf Molich. Heuristic evaluation of user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '90, page 249–256. Association for Computing Machinery, 1990. https://static1.squarespace.com/static/57d1d882e58c62c988fb0254/t/5ae8fa3b6d2a73ce72214d91/1525217854980/nielsenheuristicsCHI.pdf [Online; accessed September 3, 2020].

[8] Robert J. Lang. Origami diagramming conventions, 2011. http://www.langorigami.com/article/origami-diagramming-conventions [Online; accessed March 21, 2020].

[9] Robert James Lang. *Origami Design Secrets: mathematical methods for an ancient art*. CRC Press, second edition edition, 2012. ISBN: 978-1-56881-436-0.

[10] Robert J. Lang. Family tree of the standard bases. Published in: *Origami Design Secrets: mathematical methods for an ancient art*; p. 61.

[11] Robert J. Lang. Origami simulation, 2015. http://www.langorigami.com/article/origami-simulation [Online; accessed March 21, 2020].

[12] John Szinger. The foldinator project, 2009. http://zingman.com/origami/foldinator.php [Online; accessed March 21, 2020].

[13] Jack Fastag. egami: Virtual paperfolding and diagramming software. In Robert J. Lang, editor, *Origami 4*, pages 273–284. A K Peters, Ltd., 2006.

[14] James D Foley, Foley Dan Van, Andries Van Dam, Steven K Feiner, John F Hughes, Edward Angel, and J Hughes. *Computer graphics: principles and practice*, volume 12110. Addison-Wesley Professional, 1996.

[15] Thomas Hull. On the mathematics of flat origamis. *Congressus numerantium*, pages 215–224, 1994.