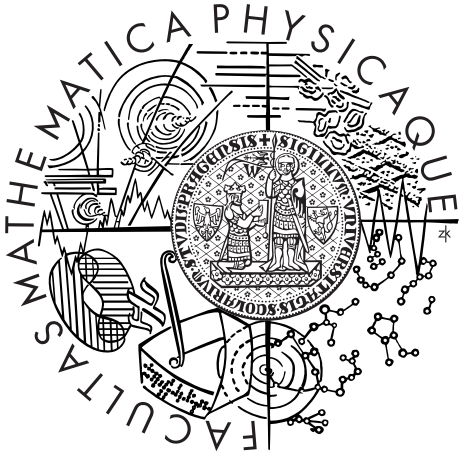
Charles University in Prague
Faculty of Mathematics and Physics

BACHELOR THESIS



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Origami diagram creator

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Supervisor of the bachelor thesis: Mgr. Martin Petříček

Study programme: Informatika

Specialization: Obecná informatika

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Poděkování.

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Název práce: Origami diagram creator

Autor: Martin Pecka

Katedra: Kabinet software a výuky informatiky

Vedoucí bakalářské práce: Mgr. Martin Petříček, Kabinet software a výuky informatiky

Abstrakt: Program Origamist si klade za cíl pomoci s tvorbou návodů na skládání origami modelů. V současné době jsou nejběžnějšími metodami pro tvorbu těchto návodů buď ruční kreslení všech kroků v obrázkovém editoru, nebo nafocení jednotlivých kroků a jejich manuální poskládání (opět v obrázkovém editoru). Origamist na toto pole přináší novou alternativu. Autor tak dostává možnost přenést posloupnost ohybů papíru, z nichž se návod skládá, do programu Origamist, jenž z nich dokáže vygenerovat několik druhů výstupu - v origamistických kruzích nejrozšířenější PDF návod, ale i návod jako obrázek (PNG, SVG), nebo dokonce jako animaci procesu skládání. Přidanou hodnotou pak je snadná možnost přeložit popisky kroků do více jazyků.

Klíčová slova: Origami, Java3D, skládání papíru, návod

Title: Origami diagram creator

Author: Martin Pecka

Department: Department of Software and Computer Science Education

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Abstract: The main target of the Origamist application is to aid with creating origami diagram manuals. Recently, the most common methods for creting those manuals are drawing of the steps in an image editor, or taking photographs of the folded steps and composing them together (again in an image editor). What Origamist brings is a new alternative to these methods. The manual's author gets the possibility to transfer the sequence of paper folds the manual consists of to the Origamist application, which is able to export several types of output - the most favourite (among origami folders) PDF manuals, but also image manuals (as PNG or SVG), and even as an animation of the folding process. There is also the added value to translate the steps' descriptions to several languages.

Keywords: Origami, Java3D, paper folding, diagram

Contents

Introduction

Everyone who has ever tried to fold an origami model knows how important it is to have a *good manual* describing the steps of the folding process. A good manual consists of lots of images (generally one image per step) and their descriptions.

Why are the manuals needed? It is too hard (if not impossible) for most people to guess the folding process by only seeing the result shape. And this is even harder if you only see the result as a 2-dimensional image on screen or paper. Thus, several methods to aid people with the folding process were introduced.

The most practical help method is learning from someone who knows how to fold the desired model. This method has two disadvantages - a man can forget what he has learnt, and, in most cases, there is simply nobody who knows how to fold the desired model (except in origami communities). Therefore *paper manuals* were invented. They are (conceptually) eternal and are relatively easy to obtain (in books or on the Web). They have another disadvantage - if some steps are unclear in the manual (which happens not so infrequently), there is no other help. The last (relatively new) means to learn the folding process are *video tutorials*.

In the paper manuals (or bitmap image manuals, we will call both of them 'paper' manuals) there are some established graphical marks that indicate the operations to be done with the paper in the step. We will discuss these marks in higher detail further in the text. The marks cover the most of operations one would like to do with the paper, but their meanings aren't fixed and unambiguous, which can lead to lack of clarity of the manual.

'Paper' and video manuals share one more disadvantage, too. They aren't *simply editable* by other people. The 'paper' manuals are either printed or distributed as PDF or image files, and these aren't simply editable (PDF editors exist, but aren't widely used; editing an image manual involves some non-basic knowledge of computer usage). Video editing is even more difficult. So, ways to edit these manuals exists, but none of them is straightforward.

Origamist brings a new alternative to those types of manuals. It presents the concept of 'live' manual. Each folding step is represented as a 3-dimensional model, which the user can view from different viewing angles and zoom levels. Furthermore, everyone can simply edit the model in the Origamist editor. It doesn't matter if the user just wants to add a translation of the steps' descriptions, edit existing step descriptions or if he wants to add some more steps, all of these activities can be done straightforward in the editor.

Also, all of the previously mentioned types of origami manuals (except personal assistance) can be exported from the Origamist application. Only the exported animation has no sound track, which is an important part of video tutorials (but it is possible to add this functionality, also the data model can be simply modified to store this type of descriptions).

1. What is origami?

Origami is the name of an ancient Asian art of folding various figures and shapes from a piece of paper.

"Whether it is called 'zhe zhi,' as it is by Mandarin-speaking Chinese, or 'chip chee,' as Chinese who use the Cantonese dialect call it, or by the Japanese name 'origami,' it is generally agreed that the art of paperfolding originated in China perhaps before the 6th century." [1, p. 123]

The traditional Japan origami focuses mainly on animal figures and flowers. You could know the most famous origami animal - the crane. It is considered as a sample of the traditional technique.

In recent times, hundreds of other origami models can be found, including boxes, decorations and ornaments, envelopes, abstract things and much more. [2]

1.1 The rules of traditional origami

There aren't much constraints in the traditional origami. Everyone can fold whatever his fantasy invents, but to call the model a traditional origami, there are these rules: [3]

- To begin with a single square sheet of paper.
- Not to tear or cut the sheet of paper.
- Not to use glue.

And that's it. No more constraints on what can be done. This is also the set of rules Origamist tries to hold (in fact, it allows non-square papers).

1.2 Other kinds of origami

Besides the traditional origami, there are several other types, differing in what is allowed or disallowed. Here is a short list of some other techniques:

- *Modular origami*, which allows to use and combine multiple sheets of paper. [4]
- *Action origami*, which creates figures whose parts are moveable, so they can be used as toys. [5]
- *Pureland origami*, which only allows one fold to be done at once, and thus disallows folds like reverse folds or rabbit folds. This type of origami is suitable for beginners, children and disabled people. [6]
- *Kirigami*, which allows cutting the paper and using glue. Kirigami is mostly used to make decorations. [7].
- *Technical origami*, which develops the models based on computer-generated crease patterns[1]. [8].

[1] More on crease patterns can be found further in section 1.5

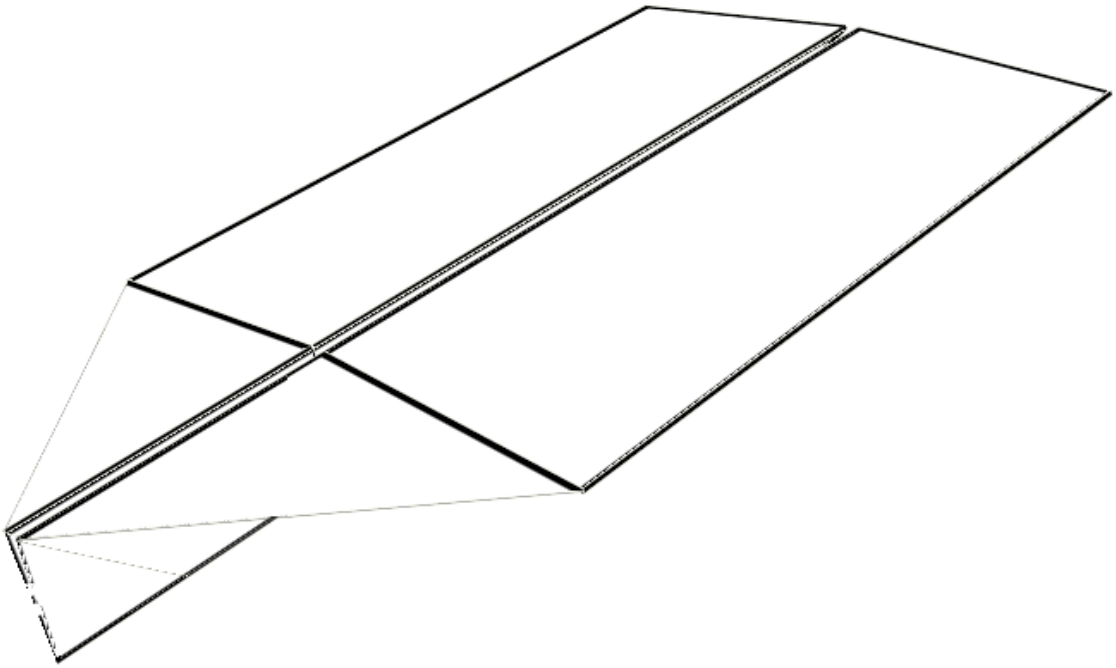
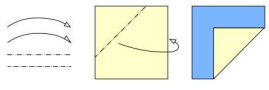


Figure 1.1: Origami model of paper plane

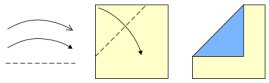
- *Mathematical origami*, which is just abstract and is used for some mathematical and algorithmic proofs.
- *Rigid origami*, which is a subset of mathematical origami and tries to find answers to the question "If we replaced paper with sheet metal and had hinges in place of the crease lines, could we still fold the model?" [8].

1.3 Basic folds

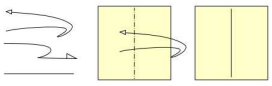
In this section, some basic fold types will be described, along with the common marks for them. Sample images are taken from [9], the steps descriptions are inspired by [2].



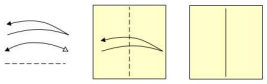
Mountain fold. This is a simple fold which bends the paper in the direction 'from the viewpoint'. An arbitrary angle can be specified for this type of fold.



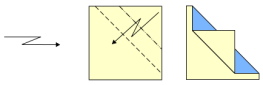
Valley fold. This is a simple fold which bends the paper in the direction 'towards the viewpoint'. An arbitrary angle can be specified for this type of fold.



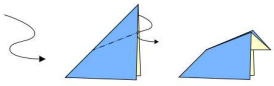
Mountain fold and unfold. This fold just makes a mountain crease on the paper. After doing it, the paper has the same geometry as before, but the crease has required moving the paper. This is mainly used for creating reference creases.



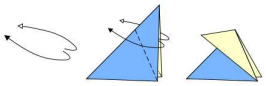
Valley fold and unfold. This fold just makes a valley crease on the paper. After doing it, the paper has the same geometry as before, but the crease has required moving the paper. This is mainly used for creating reference creases.



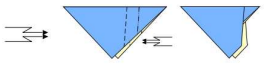
Thunderbolt fold. A double fold, one of the folds is mountain, the other is valley An arbitrary angle can be specified for both folds (a different one for each of them).



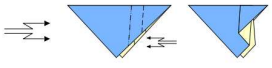
Inside reverse fold. Tuck a tip of a flap[2] inside. Uses two mountain folds for side creases, and a valley fold for the inner centre line. For every paper configuration, there exists only one angle for the created folds which guarantees to preserve the paper properties.



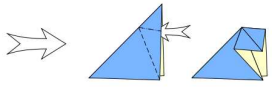
Outside reverse fold. Wrap a tip of a flap[2] around its outer side. Uses two valley folds for side creases, and a mountain fold for the outer centre line. For every paper configuration, there exists only one angle for the created folds which guarantees to preserve the paper properties.



Inside crimp fold. This is a double fold where both folds are inside reverse folds.



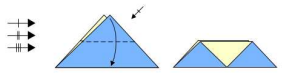
Outside crimp fold. This is a double fold where both folds are outside reverse folds.



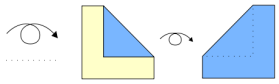
Open fold. Open or squash a flap[2] of paper. Origamist doesn't support this operation.

[2]A triangle standing out of the paper, which consists of at least two paper layers.

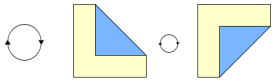
Pull fold. Unfold some previously created folds. Origamist has only partial support for this operation. Only one fold can be unfolded at a time, so eg. atomically unfolding a thunderbolt fold isn't possible.



Repeat. Repeat some previously done operations. This operation hides (for clearness) some steps and substitutes them with the repetition mark.



Turn over. Turn the paper to the other side. Origamist only supports turning around the horizontal axis of the current view, and a single turning angle - 180 degrees.



Rotate. Rotate the model of an arbitrary angle around the current view's direction axis (normal of the screen).

By using these operations, it is possible to create most of the basic and moderate origami models. The advanced models, however, often require the use of more advanced techniques. Some of them are described in [2].

1.4 More on operations' marks

As can be seen from the above images (if they aren't too small), some folds are drawn as solid lines, other are drawn as dashed lines and so on. Here are the rules for deciding how to visualise a fold line. The edges of paper are always drawn solid, a little thicker than other lines. Visible creases made in the previous steps (except the current one) are drawn by solid lines (or they can be completely omitted). Invisible[3] folds are drawn by a dotted line (.....). And finally, the creases made in the current step of the manual are drawn as dashed lines (— –) for valley folds and dash-dot lines for mountain folds (-..-..-). Note that the mountain/valley assignment is relative to the point of view.

1.5 Crease patterns

Crease patterns, although they are a very old concept, experience a boom in the latest years as an alternative to classical origami manuals. What is a crease pattern? It is the unfolded origami model, which retains the creases created during the folding process. So, basically, a crease pattern is a set of lines on a

[3]Folds hidden under other parts of paper. The visualisation using dotted lines is sometimes called X-Ray folds.

straight sheet of paper. Depending on the purpose, the directions of the folds (whether they are mountain or valley) may or may not be specified.

Why are they so popular? This may be due to two wholly different reasons. The first one is that folding a model (with known target shape) from a crease pattern is a challenge, and has no direct instructions. The second reason is that crease patterns are very important in mathematics and computational origami, which is shown in the next chapter.

2. Origami, computers and mathematics

This chapter presents some recent origami-related results in the field of mathematics or computer science, and also presents some existing origami software. Although origami is mainly art, most of these results are very interesting, and some of them have even practical use.

2.1 Computational origami

"Most results in computational origami fit into at least one of three categories: universality results, efficient decision algorithms, and computational intractability results.

A *universality result* shows that, subject to a certain model of folding, everything is possible. For example, any tree-shaped origami base, any polygonal silhouette, and any polyhedral surface can be folded out of a large-enough piece of paper. Universality results often come with efficient algorithms for finding the foldings; pure existence results are rare.

When universality results are impossible (some objects cannot be folded), the next-best result is an *efficient decision algorithm* to determine whether a given object is foldable. Here 'efficient' normally means 'polynomial time'. For example, there is a polynomial-time algorithm to decide whether a 'map' (grid of creases marked mountain and valley) can be folded by a sequence of simple folds.

Not all paper-folding problems have efficient algorithms, and this can be proved by a *computational intractability result*. For example, it is NP-hard to tell whether a given crease pattern folds into any flat origami, even when folds are restricted to simple folds. These results mean that there are no polynomial-time algorithms for these problems, unless some of the hardest computational problems can also be solved in polynomial time, which is generally deemed unlikely." [10]

2.1.1 Other computational tasks

As [10] says, there is another division of computational problems. They are *origami design* and *origami foldability* problems. *Origami design* examines the possibilities (finding the needed creases) of folding arbitrary shapes with specified properties. On the other side, *origami foldability* tries to answer if the given crease pattern is foldable into any shape.

One complete straight cut problem solves the task whose input is a polygon drawn on paper, and whose output is a crease pattern which can be folded in the way that all the polygon's edges overlap on a single line. Why one straight cut? If you cut the paper along the overlap line, you will get the polygon cut out of the paper. [10] presents results of two different approaches, both of them proving that such crease pattern can be found for any polygon.

Silhouettes and polyhedra problem takes a 2- or 3-dimensional silhouette of the desired model as its input and returns a folding of the paper resulting in the

input shape. Again, according to [10], such result always exists.

Flat foldability tries to find out if a given crease pattern (without fold directions specified) is foldable to a flat model using a consistent fold direction assignment. [11] shows a linear-time algorithm that finds such direction assignment, or tells that the given pattern is not flat foldable.

2.1.2 Existing origami software

There is a number of computer applications related to origami. Here is a list of some of them.

- *TreeMaker*[1] by Robert Lang, is a tool for designing crease patterns for given sketched shapes. The shape is basically sketched as a tree (in the algorithmic meaning of the word), thus TreeMaker. The program uses the disc packing method, described in [12].

- *Origami simulation*[2] by Robert Lang is a simple GUI tool for designing pureland origami. Since 1992 the development has been stopped, and it only works on PowerPC Macs.

- *ORIGAMI Playing Simulator in the Virtual Space* by Shin-ya Miyazaki, Takami Yasuda, Shigeki Yokoi and Jun-ichiro Toriwaki. Another interactive GUI tool for origami model folding, was presented in [13]. Although this seems to be the most capable GUI tool for origami, I couldn't test it, because the given paper doesn't provide a link to the application.

- *Doodle*[3] by Jérôme Gout, Xavier Fouchet, Vincent Osele, and volunteers. Doodle is a tool for generating origami diagrams from the given ASCII text instructions. This program produces nice diagrams, but needs a lot of additional information in the input files (eg. it is often needed to rotate some paper parts by an explicit command, because the fold commands just create the associated fold lines).

- *ORIPA*[4] by Jun Mitani. ORIPA is interactive GUI tool for designing crease patterns. It also provides an estimated preview of the folded model.

- *Computational Origami System Eos* by Tetsuo Ida, Hidekazu Takahashi, Mircea Marin, Asem Kasem and Fadoua Ghourabi. This software introduced in [14] is a non-interactive tool for folding origami models and automatic proving some conclusions about the constructed models. EOS is written in Mathematica.

2.2 Origami in other sciences

Mathematics and computer science aren't the only disciplines origami brings benefits to. Here is a list of other uses of origami theory:

[1] `http://www.langorigami.com/science/treemaker/treemaker5.php4`

[2] `http://www.langorigami.com/science/origamisim/origamisim.php4`

[3] `http://doodle.sourceforge.net/about.html`

[4] `http://mitani.cs.tsukuba.ac.jp/pukiwiki-oripa/index.php?ORIPA%3B%20Origami%20Pattern%20Editor`

- *Stents* in medicine. Stents are small tubes used to reinforce or broaden clogged veins and arteries. Since they are transported to their destination through veins and arteries, they need to be in a folded state, then they can be transferred to the right place, and unfolded. A waterbomb base[5] is mainly used for stents. [15]

- *Eyeglass space telescope* needed the help of origami theory master Robert Lang[6] to invent a method of folding a large telescope into a space satellite. [16]

- *Space project SFU* of Japanese space organization JAXA used Robert Lang's origami experiences to efficiently fold and unfold a solar panel array in the open space. The fold they used is called Miura map fold[7].[17]

- Origami design techniques were used by a German company to simulate effective *packing of airbags* into car steering wheels. [18]

- Origami techniques helped with the development of *3D solar panels*, which increase the productivity of solar panels and have the advantage of not having any movable parts that can get broken. [19].

[5] One of the standard origami bases, which are just a series of steps shared by many models in the beginning.

[6] `http://www.langorigami.com/science/eyeglass/eyeglass.php4`

[7] `http://en.wikipedia.org/wiki/Miura_map_fold`

3. Origamist basic facts

Here I will present the basic structure of Origamist and the technologies used.

3.1 Basic structure of Origamist

3.1.1 Two parts of the application

Origamist isn't just a single application. It consists of two standalone parts.

Origamist editor provides the tools needed to create new origami diagrams and manuals. So various folds can be added to existing models, or a brand new model can be created. Also the metadata of the model can be edited.

Origamist viewer is a viewer application, that can only display formerly created diagrams. Its main target is to be used as webpage applet, so that the visitors of an origami site can comfortably browse the models the site offers. Although the viewer isn't primarily meant to create the manuals, it has the same export possibilities as the editor, so every user of any part of Origamist is able to create the manuals in various export formats.

3.1.2 Programming language and deployment technologies

Origamist has been written mainly in Java[1]. There were several reasons for this decision. Firstly, Java is a multiplatform language ([20]), which is a basic requirement due to the intended viewer usage. Secondly, Java applications can be integrated directly into a webpage (using the Java Web Start or Java Plugin), which rapidly simplifies the access to the application. The third most important reason was that no platform-specific code has to be written (at least not in Origamist[2]), which greatly simplifies the programming work and allows to concentrate on the core business.

Java provides multiple solutions to application deployment, and Origamist uses these three (or four) of them:

- The first one is a standard Java application packed into a single JAR archive file[3]. So, anyone can run the application by moving to the folder containing the JAR and typing:

  ```
  java  -jar  OrigamiEditor.jar
  ```

- Another possibility is to include the application into a webpage as Java applet using the standard applet code. See 4.7 for a sample webpage.

- A similar one is to include the application into a webpage as Java applet using the *Next-Generation Java Plugin Technology* introduced into Java in version 6u10 ([21]). See 4.8 for a sample webpage.

[1] Several other languages have been used, such as XSLT and XML, but these are only scripting and tagging languages not providing the core functionality.

[2] Otherwise, Java allows to use platform-specific code, but doing so isn't a common practice in Java.

[3] Application libraries are standalone files, too.

- The last possibility is to launch and install the application through the *JNLP protocol*[4]. This protocol allows Java applications to be downloaded and installed on the target machine as standalone applications, so the end user can eg. make shortcuts to these programs and utilise them offline. JNLP also provides a way of automatic updates of the downloaded software. See 4.9 for a sample JNLP file that launches Origamist viewer.

3.1.3 Data files

Origamist saves all its data[5] in XML text files. There are two types of files Origamist recognises.

Diagram files

Diagrams are XML files with the *.xml* file extension having their root element in a model-specific namespace. For technical details on this, consult the programmer's manual.

The XML file contains all information needed to render the model and export the manuals, and also some metadata[6].

These files follow the convention of not storing any 3-dimensional data, so all folds are defined only by their position on the crease pattern[7].

Listing files

Origamist recognises one special type of XML files - those having their name *listing.xml* and having their root element in the listing-specific namespace. For technical details on this, consult the programmer's manual.

Listing files are used by the viewer to define and organise whole sets of models. The listing files have a tree structure, where every model can be attached to a named category. Some excerpts of the models' metadata are also saved in the listing files, so that it isn't required to download the whole model to see its name or thumbnail.

Origamist provides no complete support for creating these files. Here are two main reasons. These files are supposed to be automatically generated on a server providing the models (this is the expected use case). Moreover, a partial support for manual creation of these files exists. If the user loads a whole directory structure into the viewer, it automatically creates categories for matching subdirectories using their names. The listing can then be saved from Origamist viewer, however it doesn't support extended features like fully localised category names[8].

[4] `http://www.oracle.com/technetwork/java/javase/index-142562.html`

[5] Except user preferences which are stored in the system registry.

[6] Like the model's name, author's name, description of the model, paper formats, licensing information and so on.

[7] More on this topic in the programmer's manual, section ??

[8] These can be added manually to the exported listing file.

3.2 Interesting technologies used in the project

The most interesting technologies Origamist uses are listed here, for a full list of technologies and libraries, refer to the programmer's manual.

3.2.1 Git

Git is a distributed versioning system which I have used for recording the work progress. It is easy to use and does its work well. Sometimes, the ability to amend last commit[9] is useful and helps keeping the repository clean. Even though nobody else used the repository and I have been the only commiter, the repository gave me bigger freedom in what I do with the code. The whole Git repository is on the attached CD.

3.2.2 JAXB

Java And XML Bindings[10] is a library for mapping XML files to Java objects and vice versa. It not only provides the mapping, but, since the XML files' schemata and the Java classes carry redundant information, offers to generate either the schemata or the Java classes.

I have chosen to write schemata for the data files (they are in XSD[11] format), and JAXB[12] generates the Java classes automatically. The generated classes are plain Java objects annotated by some special annotations, and they follow the Bean pattern[13]. Advantages of this approach are significant if there is the need to add some fields to the data files[14], just edit the XML schemata and the Java classes will be updated to be consistent with the schemata without any additional effort.

Among other advantages I would like to stress the simplicity of the Java $\leftrightarrow$ XML conversion[15]. It basically consists of just a few lines of code[16], but allows a great deal of customisation if it is needed.

Nevertheless, JAXB has one disadvantage. Since the classes are auto-generated, there is no chance of adding further functionality directly to those files, so they always remain plain 'data envelopes'. Although this may seem to be a big disadvantage, there is a near elegant solution to this problem. See ?? for detailed information.

[9] Additionally change the files or comment of the last commit.

[10] `http://www.oracle.com/technetwork/articles/javase/index-140168.html`

[11] XML Schema Definition, which is a promising successor of the old DTDs

[12] Using its tool XJC

[13] `http://download.oracle.com/javase/tutorial/javabeans/whatis/index.html`

[14] Which is often during the initial development, but no so frequent in further 'life' of the application

[15] JAXB has the terms marshalling for Java $\rightarrow$ XML, and unmarshalling for XML $\rightarrow$ Java

[16] Refer to ~services.JAXBListingHandler and ~services.JAXBOrigamiHandler

3.2.3 Java3D

Java3D[17] is a powerful Java library for displaying and creating 3D graphics. It provides two basic modes of work — a 'direct' mode[18] which makes working with Java3D much like working in OpenGL; the other mode is more object-oriented[19] and provides an easy-to-use interface for composing the 3D scene, which means that most of the computations are hidden before the programmer. Java3D integrates nicely with the Swing[20] GUI [21] library.

Since 3D graphics is basically a very low-level work, Java3D needs some native libraries to run. This effectively narrows the list of platforms Origamist will run on to the list of Java3D supported platforms. Fortunately, a Java3D implementation is available for most of the Java supported platforms [22]. As native libraries cannot be distributed in the standard way as JAR libraries are, they require special handling. Refer to the programmer's manual for more on this.

3.2.4 Forms

JGoodies Forms[22] is a Swing layout manager. Swing provides some layout managers in the standard JRE[23] distribution, but they either aren't much flexible, or are overly complex. JGoodies Forms allows the programmer to define a grid[24] on the current window or component, and put other components into this grid.

3.2.5 Batik

Batik[25] provides a simple way of generating SVG[26] and PDF files in Java. It has other SVG-related capabilities, too, but they are unimportant for this project.

3.2.6 Ant

Apache Ant[27] is a Java build tool. Its design is very robust, it allows to trigger innumerable different tasks during the build, so that everything needed to build and deploy a complex Java application is to run command

```
ant
```

in the command line from the application's base directory. Ant even supports plugins[28].

---

[17] `http://java3d.java.net/`

[18] Called 'immediate mode' in Java3D.

[19] Called 'retained mode' in Java3D.

[20] `http://download.oracle.com/javase/tutorial/uiswing/start/about.html`

[21] Graphical User Interface

[22] http://www.jgoodies.com/freeware/forms/

[23] Java Runtime Environment, the minimal installation of Java needed to run most Java applications.

[24] The use of grids is very common in UI design, but JRE doesn't provide any layout manager capable of working with more complex grids.

[25] `http://xmlgraphics.apache.org/batik/`

[26] Scalable Vector Graphics

[27] http://ant.apache.org/

[28] And this project uses some of them.

4. Origamist's algorithms & data structures

This chapter covers the most important computational algorithms, data structures and programming approaches the program uses.

4.1 Representation of the origami model

4.1.1 Triangles and layers

The model is stored simultaneously as a 3D model and 2D crease pattern. Both these models are represented by a set of triangles. Every 2D triangle corresponds to exactly one 3D triangle, and thus we will call the 2D triangle as the 'origin' or 'original' of the 3D triangle (because in the very first step, the corresponding 2D and 3D triangles are the same). The triangles are grouped to so called *layers* of paper.

Definition. *A* layer of paper *is a nonempty set of triangles meeting the following conditions:*

- *All triangles have their normals pointing in the same direction*[1].
- *The original triangles form a single, nondegenerated and connected polygon*[2] *on the crease pattern.*
- *The 3D triangles form a single, nondegenerated, connected and planar polygon.*
- *Every triangle belongs to exactly one layer.*

As a consequence of this definition, we see that the whole paper model can be parcelled into layers. A layer of paper can be imagined as the largest straight part of the paper bounded by creases or edges of the paper[3].

What is the term of layer good for? A layer is always the smallest unit of paper that can be moved, bent, or rotated. If a fold would go through the interior of a layer, a crease is created in the layer and it is subdivided into more smaller layers[4].

4.1.2 Fold lines

Although it is not necessary to hold all the fold lines in memory[5], it shows that it is helpful to have a quick access to them. So, every triangle remembers all the

[1] This trivially holds for the original triangles

[2] But possibly non-convex.

[3] But it is allowed for a layer to have its boundary at a crease of angle 0°. This means it doesn't always have to be the largest straight part, but it is guaranteed that a layer doesn't have its boundary somewhere 'inside' (the boundary is always an edge of the paper or a crease).

[4] Convex layers always split to 2 parts, but nonconvex layers can generate more sublayers

[5] All fold lines could be just signalised by layers' boundaries.

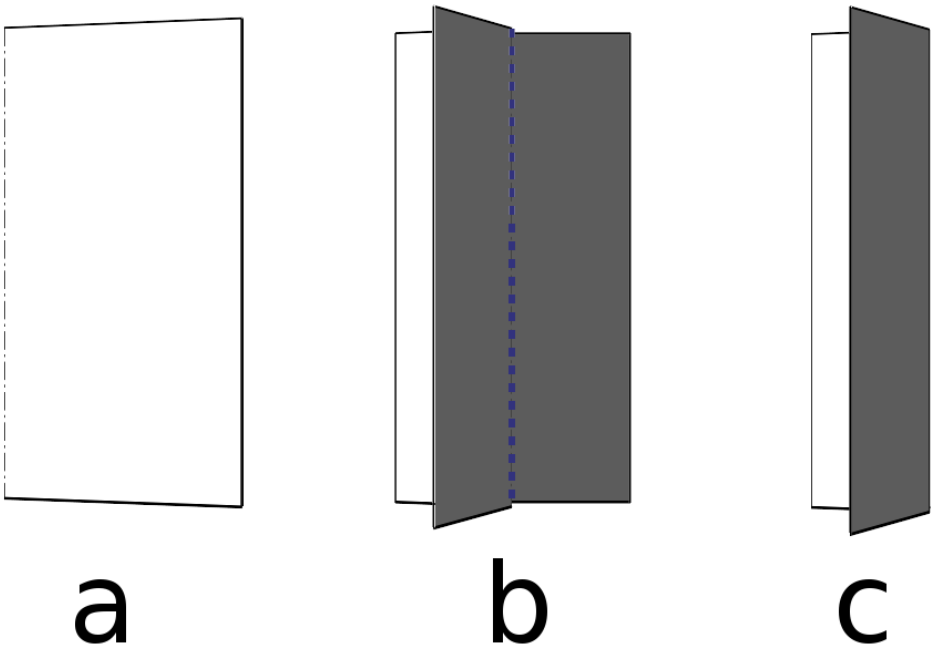


Figure 4.1: Different layers that can be bent

fold lines it lies along, and all fold lines have links to the triangles lying along them. Moreover, the folds remember the direction of the fold (mountain/valley), so it can be used later in generating crease patterns or for displaying the just done operations (as described in 1.4). They also remember their 'age' in the number of steps they were last 'touched' (used in a fold). The age can be used for blending old and probably unimportant creases.

4.1.3 That's all we need

The triangles, layers and fold lines are all we need to know to be able to correctly render and alter the model. More precisely, only 3D triangles and fold lines are needed, but layers and 2D triangles are needed for interaction with the model.

4.2 How to represent the operations?

Most operations consist of a set of lines, probably an angle or two, and... No, that isn't sufficient. Look at figure 4.2.

The last thing to be specified is which layers of paper should be bent. As you can see in the figure, no layers are bent (a), the first layer is bent (b), or both layers are bent (c).

So we have it - lines, angles and layers. Lines and angles are easy to represent and address. Layers are worse. There is no unambiguous designation of the

layers other than assigning them some artificial keys[6]. But what keys? Should we index the layers according to the order they have emerged? That sounds really unnatural and like a bad design idea[7].

I have finally found a naturally-looking set of keys. The mapping is based on the active line[8] (the line the currently created fold will be folded along). The line always lies in a layer. So take this layer and make a stripe perpendicular to it and having its border lines at the endpoints of the active line (it's actually always a segment). Then record all intersections of this stripe with another layers not parallel with the stripe[9]. Sort the intersections by the distance from the viewer[10] (more precisely sort by the distance of their centres, because the intersections can have arbitrary angles towards the stripe and it wouldn't be clear what point to measure the distance from). Now, assign indices from 0 upwards to the sorted layers.

Although this key-mapping algorithm looks complex, it just does what people do naturally[11].

So, in the data files, it is sufficient to first define the line to fold along, and then these keys can be used to describe the layers that will be bent. Figure 4.2 illustrates this.

4.3 How to bend the paper?

4.3.1 Which folds to implement?

We will show that the ability to perform valley and mountain folds (let's call them basic folds) is sufficient for making any operation of those listed in 1.3.

It is possible that during the decomposed operation the paper will get into inconsistent state (eg. it can intersect and tear), but after completing the whole operation, it will be either consistent, or the operation was invalidly specified.

Thunderbolt fold is just a composition of two basic folds. Do the first one, then the second one, and that's it.

Inside/outside reverse folds can also be substituted with two basic folds (here the paper will be torn in between of the operations). It's worth noting that reverse folds don't need to specify angle of rotation, because there is only one nontrivial angle for which the operation will be valid (otherwise the paper would

[6] We don't consider the option to label layers by themselves, because this is just useless - who would like to see the full list of triangles to be rotated in the diagram file? There must be a better option.

[7] What if the bending algorithm got changed and the order of layers' emerging with it?

[8] It is never needed to select layers without the need to select a line altogether, so this makes sense.

[9] Bending a layer parallel with the stripe would mean bending a layer perpendicular to another layer we will bend, which makes no sense. Although such folds are possible, it would be better to divide them into two separate folds.

[10] Since fold directions are dependent on the viewpoint, this brings no new dependencies to the algorithm.

[11] How would I tell another person what layers to bend? I'd tell something like 'Bend the first four layers,' or 'Bend the topmost and bottommost layers.' Similar instructions can be found in many origami manuals. All these instructions refer to the same order of layers this algorithm defines.

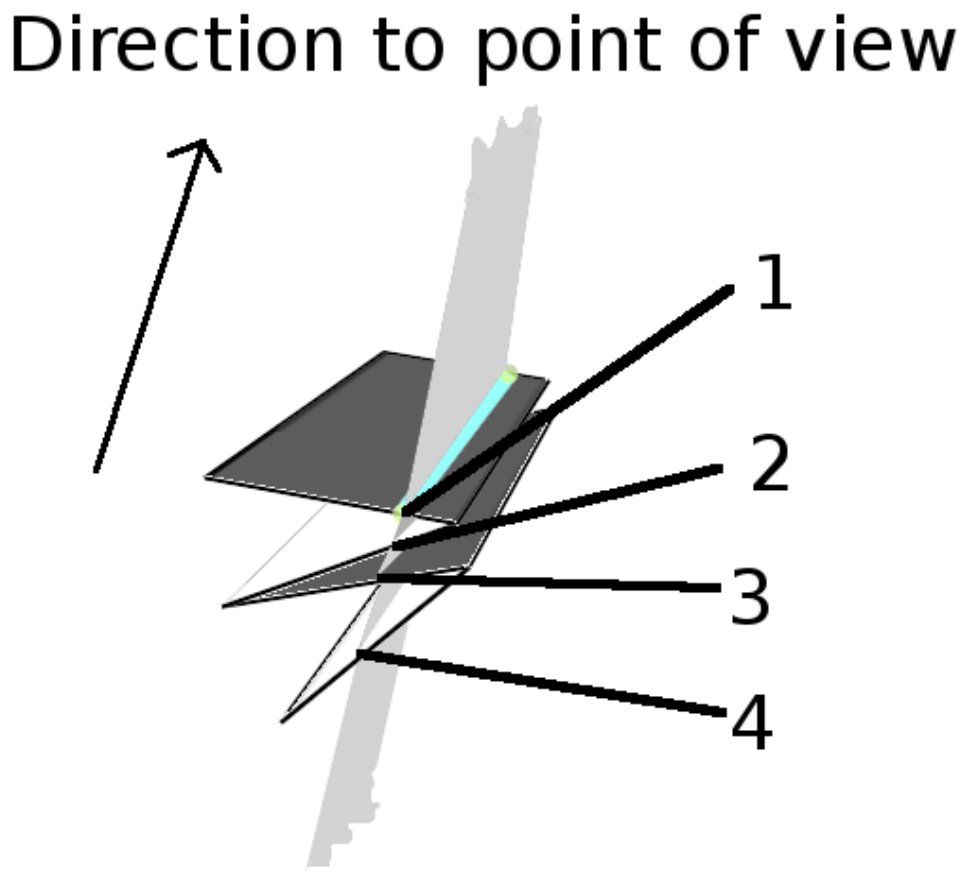


Figure 4.2: The indices mapped to layers according to the active line (azure on the image).

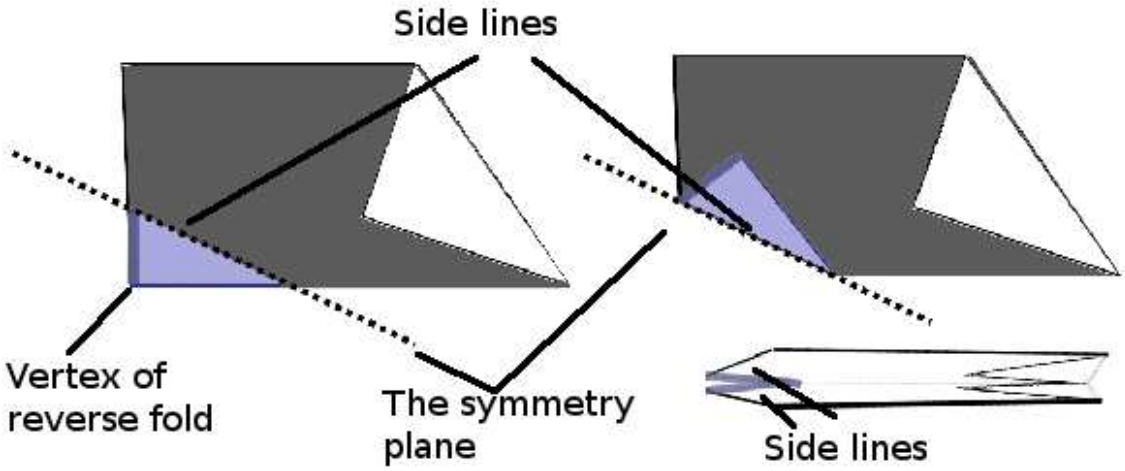


Figure 4.3: The symmetry of inside reverse fold.

get curved). The angle is determined from the symmetry that reverse folds define. The symmetry is illustrated in figure 4.3

Inside/outside crimp folds are just double reverse folds and no additional paper tearing or intersecting can happen.

The pull operation also just rotates one part of the paper around the unfolded crease, so basic folds are sufficient.

The open operation is the most difficult, it could involve more layers to be rotated separately, but again, all of these steps will only be rotations of the paper around an axis (or multiple aces).

4.3.2 The basic fold operation

Let's get to the core of the folding. The operation is divided into two steps — triangle subdivision plus fold line creation (let's call it 'part 1'), and bending plus subdividing layers (calling it 'part 2').

Making creases

Firstly, the layers involved in the triangle subdivision are determined by the algorithm from 4.2. All triangles having a fold line going through their interior are subdivided into two or three smaller triangles. All triangles carry the list of their neighbors, so these lists are updated. These triangles copy the appropriate fold line data of the old triangle and add the new fold line to their fold line data. Internally, the direction of the fold is taken relatively to the triangle's normal[12]. So, this has been the first part of the process.

Bending

Then the bending comes to the scene. We need to detect all layers that will be rotated (that are not only those found in part 1, but also all layers 'more distant' from the fold line but firmly connected to any rotated layer).

[12]Here it is important to mention that the triangle subdivision process must retain the same normal direction, which is no problem.

Finding all layers to be rotated

I use an eager algorithm for finding these layers. I begin with the layers from part 1. I subdivide them into more smaller layers and pick those that are to be rotated[13]. Then I go to all neighbouring layers and check if they can be added to the to-be-rotated set. What are the terms for adding a layer's neighbour? Firstly, a newly added fold line mustn't lie between these two layers. If it did, one layer would surely have been in the part we want to rotate, whilst the other one would have been in the part we want not to rotate. And secondly (which is nearly implicit from what has been said former), the layer must be a neighbour of an already rotated layer. These two conditions are sufficient to find the right set of triangles to rotate. And then comes the easiest part - taking all the layers and rotating them around a single axis.

4.3.3 Pitfalls

There are still some unanswered questions on the folding algorithm. Let's take a look on them.

What 'half' to rotate?

At the beginning of part 2, how do we choose the parts of the subdivided layers we want to rotate? Well, that's a question. We define a halfspace and take all layers the halfspace contains (the halfspace's border plane is the same as the plane of the stripe constructed for layer selection). What part of paper should 'stay' and what should rotate? Geometrically, the results are the same. But the real 3D coordinates of the points will differ. One possibility is to let the user to select a point in the 'half' of the model he wants to be rotated (these points are called 'refPoints' in the application). Otherwise, we have to guess. Here is a little heuristic. Firstly, we just select any of the 'halves' and find the layers to be rotated. But then the heuristic looks at the quotient of rotated and non-rotated triangles, and rotates the smaller of these two sets[14].

Layers in composite operations

The layer indexing and selecting algorithm fails while doing the second (third, fourth, ...) basic operation during a composite one (eg. a thunderbolt fold). We could define the layers using this algorithm after doing each substep, the disadvantage is that the paper doesn't have to be in consistent state between the substeps. So another method for layer selection is applied to composite folds. The first substep has its layers of operation defined normally by the indices. After doing the first substep, it passes the rotated layers to the input of the second substep, and so on. This practice is based on the fact that all the composite operations work ordinarily with the same number of rotated layers for all substeps[15], so it perfectly matches the real folding process.

[13] This will be discussed later.

[14] This is based on the thought that the user mainly wants to rotate the smaller parts of paper, whilst the large remainder of the model should stay on place.

[15] And from a human point of view, these are 'still the same layers'.

Angle of rotation for reverse folds

How to determine the angle of rotation for a reverse fold? We have already shown the reverse fold symmetry in figure 4.3. The symmetry is drawn as a line in the figure, but in fact it is a plane symmetry (the plane goes through the two side lines). So, to determine the angle, we just take the image of the reverse fold vertex (marked in the figure) and compute the angle between the image and the original.

Multiple layers in the same plane

Origamist could handle better the case when multiple layers of paper are folded so that they lie in the same plane. In this case, the ordering of layers for a fold operation isn't precisely defined. It doesn't do problems in the case of interactive model creation as long as the algorithm for layer indexing indexes the layers in the same plane equally. It will be needed to implement something like [13] has — the layers folded into a single plane remember their relative ordering, so it is possible to unambiguously identify them. This would also have better effect on the paper intersection check.

4.4 Paper geometry checks

Origamist implements two checks of the paper geometry. The paper tearing check, and paper intersection check.

4.4.1 Paper tearing check

This check is made very easily. Since all triangles know both their 2D (original) position and their 3D position, all that is needed to do is to iterate over 2D neighbors[16] and check if they also are neighbors in 3D.

4.4.2 Paper intersection test

This test is rather more demanding. To check if the paper doesn't intersect, we need to find all mutual intersections of layers and check if they are at most 'touching'. Layers lying in the same plane are considered touching, layers with distinct parallel planes cannot intersect. The last possibility is that the layers' planes have a single common line. If the line isn't contained in any of the layers, the layers don't intersect. Finally, in the remaining case, we must check the touching. This is effectively done by constructing a halfspace with its border plane in one layer's plane, and checking if all of the other layer's points not lying in this border plane lie only on a single side of the defined halfspace (either all lie in the halfspace or none of them lies in it). Then the same is done with the halfspace's border plane being the second layer's plane.

This check runs asymptotically in $O(n^2)$, but practically it just consists from a small number of computations, and the count of layers isn't a very large number in basic and moderate origamis.

[16] Since the triangles carry the lists of their neighbors, this is really simple.

4.4.3 When to run these checks?

These checks cannot be run directly after a basic fold operation is done, because some composite operations need to get the paper into an invalid state during their operation. If we could do the check after the basic folds, it would simplify the checks, because it would be sufficient to take only the rotated layers into account. But since multiple basic folds can be done before the checks, we rather run the checks for the whole model[17].

4.5 Delayed operations

In Origamist editor, all operations are completely done as soon as they are defined. However, this is not suitable for the viewer and for manual generation. The classical origami manuals divide most operations into two steps. In the first one, only the creases the operation creates are marked. All the bending is done in the second step[18].

The first idea I had was just not to perform the bending at all in the first step. But that would work only if just one simple operation is permitted per step (pureland origami). If multiple basic operations were done in a step and the bending weren't performed, the layer indexing algorithm could fail for the second and subsequent folds. Also, eg. the thunderbolt fold uses the list of layers rotated in the first substep to define the list of layers to be rotated in the second substep.

So, another approach is needed. Before the very first operation is done in a step, all triangles are instructed to save their current 3D position (every triangle has a special data field for this purpose). Then all bending operations are done normally, and after the last operation has been performed, triangles just restore their original positions — but the created creases remain, which is exactly the desired result.

4.6 Struggling with floating-point arithmetic

The whole Origamist application is based on computing with floating-point numbers. Because a high precision is needed in the application, the Java type *Double* is used. But even this isn't sufficient for the operations to be precise. I try to have all the model's vertices' coordinates between -1 and 1, because Double has the highest density in this interval, so it is supposed to have the least rounding errors.

All comparisons are done by checking if the absolute value of the difference of the compared numbers is less than a specified ϵ. What ϵ to take? I use 10^{-6} as it has a good mapping to the reality. As the longest side of the paper has the length of 1 unit (usually about 20 cm in physical world), the epsilon corresponds to $2 * 10^{-7}$ meters. Due to the thickness of a paper sheet (being something like 10^{-4} meters) this ϵ value seems to be appropriate.

[17] It could be sufficient to accumulate the rotated layers for all the substeps and do the checks for them.

[18] This is for better clarity. It is simpler to show a fold's direction when it lies in a straight plane, than if it goes along an already bent crease.

This ϵ is thus good for operations on the paper's vertices. But what about comparing angles or other paper-unrelated numbers? Well, for simplicity, Origamist uses the same ϵ everywhere, but the precision of computations would be better if the ϵ were scaled according to the unit it is used for. [23] provides some hints on how could this be done better.

4.6.1 ϵ-comparing maps?

I had the idea to develop a map (a tree) that could store 3D points or lines and search among them to return those that are ϵ-equal to a given search key[19]. Classical approaches aren't successful. Hashmaps don't work because ϵ-equal items don't have to have equal hash code, and there is no suitable mapping that could assign the hashcodes reasonably[20]. Classical binary search trees also fail quickly with floating-point numbers.

I had the idea to use multidimensional interval trees, which could work for this purpose. Or R-trees could also work. But instead of implementing these complex data structures[21], I have found out that they aren't needed. All the information that seemed to need these maps could be stored somehow else. Eg. the list of triangles' neighbors is stored inside the triangles and so on. This finally seems to be the most effective approach.

4.6.2 What about rational numbers?

The use of rational numbers for all computations would greatly increase the precision of the computations. But there are some facts that disallow this. The main problem are angles[22], which generally have irrational sines and cosines (and those are used in computing the rotations). So, if we restricted to angles with rational sines and cosines, it maybe would be possible to switch to rational numbers. But then we couldn't represent the often used angles like 45° (which has both sine and cosine equal to $\sqrt{2}/2$). So this question remains open.

[19] In order to store the neigbors lists and such things outside the triangles.

[20] Partitioning the space to ϵ-equal blocks doesn't work, because if you put a number from the lower bound of one block into the map and then search for a number even smaller, the search will fail even if the distance if these items is less than ϵ.

[21] Java doesn't provide a default implementation.

[22] Because Origamist doesn't need any other 'irrationalizing' operations like log or square roots.

Závěr

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Attachments

4.7 A sample webpage displaying Origamist as a standard Java applet using the old Java Plugin

```
<html>
    <body>
        <applet code="cz.cuni.mff.peckam.java.origamist.gui.viewer.
            OrigamiViewerBootstrapper"
              width="800"
              height="600"
              archive="
                lib/log4j-1.2.16.jar,
                lib/j3dcore.jar,
                lib/j3dutils.jar,
                lib/vecmath.jar,
                lib/jaxb2-basics-runtime-0.6.0.jar,
                lib/forms.jar,
                lib/batik-anim.jar,
                lib/batik-awt-util.jar,
                lib/batik-bridge.jar,
                lib/batik-codec.jar,
                lib/batik-css.jar,
                lib/batik-dom.jar,
                lib/batik-ext.jar,
                lib/batik-gvt.jar,
                lib/batik-parser.jar,
                lib/batik-script.jar,
                lib/batik-svg-dom.jar,
                lib/batik-svggen.jar,
                lib/batik-transcoder.jar,
                lib/batik-util.jar,
                lib/batik-xml.jar,
                lib/itextpdf-5.1.0.jar,
                lib/JPEGMovieAnimation.jar,
                lib/pdf-transcoder.jar,
                lib/xml-apis-ext.jar,
                OrigamistViewer.jar
             ">

            <param name="files" value="diagrams/paper_plane.xml
               diagrams/advanced_diagram.xml diagrams/diagram.xml" /
               >
            <!-- These are the files to be displayed at startup. -->

```

```
            <param name="startupMode" value="page" />
            <!-- Startup mode of the page, either "page" or
            "diagram". -->

            <param name="java_arguments" value="-Xmx1024m" />
            <!-- Require more memory than the default portion. -->
        </applet>
         </body>
</html>
```

4.8 A sample webpage displaying Origamist as applet using new generation Java plugin, if the client has installed it

```
<html>
    <body>
        <applet code="cz.cuni.mff.peckam.java.origamist.gui.viewer.
            OrigamiViewerBootstrapper"
              width="800"
              height="600"
              archive="
                lib/log4j-1.2.16.jar,
                lib/j3dcore.jar,
                lib/j3dutils.jar,
                lib/vecmath.jar,
                lib/jaxb2-basics-runtime-0.6.0.jar,
                lib/forms.jar,
                lib/batik-anim.jar,
                lib/batik-awt-util.jar,
                lib/batik-bridge.jar,
                lib/batik-codec.jar,
                lib/batik-css.jar,
                lib/batik-dom.jar,
                lib/batik-ext.jar,
                lib/batik-gvt.jar,
                lib/batik-parser.jar,
                lib/batik-script.jar,
                lib/batik-svg-dom.jar,
                lib/batik-svggen.jar,
                lib/batik-transcoder.jar,
                lib/batik-util.jar,
                lib/batik-xml.jar,
                lib/itextpdf-5.1.0.jar,
                lib/JPEGMovieAnimation.jar,
                lib/pdf-transcoder.jar,
                lib/xml-apis-ext.jar,
                OrigamistViewer.jar
```

```
            ">
34
                  <param name="jnlp_href" value="origami_viewer.
                     jnlp">
36                <!-- This is the only difference between the old
                     and new generation plugins. Listing of the
                     archive attribute and filling up params in
                     this page isn't used by the new generation
                     plugin, but it is there to work either on user
                      clients with old plugins. -->

38          <param name="files" value="diagrams/paper_plane.xml
                diagrams/advanced_diagram.xml diagrams/diagram.xml" /
                >
            <!-- These are the files to be displayed at startup. -->
40
            <param name="startupMode" value="page" />
42          <!-- Startup mode of the page, either "page" or
            "diagram". -->
44
            <param name="java_arguments" value="-Xmx1024m" />
46          <!-- Require more memory than the default portion. -->
        </applet>
48       </body>
</html>
```

4.9 A sample JNLP file to run Origamist viewer

```
1 <?xml version="1.0" encoding="UTF-8"?>
  <!DOCTYPE jnlp PUBLIC "-//Sun Microsystems, Inc//DTD JNLP
     Discriptor 1.5//EN" "http://java.sun.com/dtd/JNLP-1.5.dtd">
3 <jnlp spec="1.0+" codebase="http://www.ms.mff.cuni.cz/~peckam/
     origamist" href="origami_viewer.test.jnlp"><!-- codebase must
     point to the !absolute! location of the JNLP file, otherwise
     the newest Java versions won't run it! -->
    <information>
5     <title>Origamist viewer</title>
      <vendor>Martin Pecka</vendor>
7     <homepage href="http://github.com/peci1/Origamist"/>
      <description>A viewer for digital origami models.</description>
9     <description kind="short">An origami viewer application.</
         description>
      <offline-allowed/>
11  </information>
    <security>
13    <all-permissions/>
    </security>
15  <resources os="Windows">
```

```
    <property name="sun.java2d.noddraw" value="true"/>
  </resources>
  <resources os="Mac OS X">
    <property name="j3d.rend" value="jogl"/>
  </resources>
  <resources>
    <j2se version="1.6+" href="http://java.sun.com/products/autodl/
       j2se" initial-heap-size="128m" max-heap-size="1024m"/>
    <jar href="OrigamistViewer.jar" main="true"/>
    <jar href="lib/batik-anim.jar"/>
    <jar href="lib/batik-awt-util.jar"/>
    <jar href="lib/batik-bridge.jar"/>
    <jar href="lib/batik-codec.jar"/>
    <jar href="lib/batik-css.jar"/>
    <jar href="lib/batik-dom.jar"/>
    <jar href="lib/batik-ext.jar"/>
    <jar href="lib/batik-gvt.jar"/>
    <jar href="lib/batik-parser.jar"/>
    <jar href="lib/batik-script.jar"/>
    <jar href="lib/batik-svg-dom.jar"/>
    <jar href="lib/batik-svggen.jar"/>
    <jar href="lib/batik-transcoder.jar"/>
    <jar href="lib/batik-util.jar"/>
    <jar href="lib/batik-xml.jar"/>
    <jar href="lib/forms.jar"/>
    <jar href="lib/gluegen-rt.jar"/>
    <jar href="lib/itextpdf-5.1.0.jar"/>
    <jar href="lib/j3dcore.jar"/>
    <jar href="lib/j3dutils.jar"/>
    <jar href="lib/jaxb2-basics-runtime-0.6.0.jar"/>
    <jar href="lib/log4j-1.2.16.jar"/>
    <jar href="lib/pdf-transcoder.jar"/>
    <jar href="lib/vecmath.jar"/>
    <jar href="lib/xml-apis-ext.jar"/>
  </resources>
  <applet-desc name="Origami viewer" main-class="cz.cuni.mff.peckam
     .java.origamist.gui.viewer.OrigamiViewerBootstrapper" width
     ="800" height="600" documentbase=".">
    <param name="files" value="diagrams/listing.xml"/><!-- These
       are the files to be displayed at startup. -->
    <param name="displayMode" value="PAGE"/><!-- Startup mode of
       the page, either "page" or "diagram". -->
  </applet-desc>
</jnlp>
```