Refined Flattening Calculation of Hot Air Baloon Shape Surface Tiles

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ABSTRACT

Design of hot air balloons can benefit from computer graphics in combination with numerical methods. The balloons are usually designed using modern CAD tools where their shape is modelled in 3D space. However, the design of the 3D shape is just a beginning of a complex production process. Flattening of the designed tiles and their preparation for a fabric cut is critical for a final quality of the design. Because of a relatively small number of companies producing the hot air balloons, only a limited number of very expensive useful tools exists. This paper addresses the issues of an automatic cut design calculation based on the 3D shape and physical properties of the fabric, using advanced numerical methods combined with existing flattening algorithms.

Keywords

surface flattening, cut design, energy model, particle system, numerical system, differential equations, hot air balloon design

1 INTRODUCTION

Many products of complex 3D shapes are being manufactured from materials, such as fabrics, tins, etc., that are being produced as flat ones. Therefore, preparation of the manufacturing process – "surface flattening" is an important process in many applications, in our case manufacturing of hot air balloons. The hot air balloon envelope, its design, shape, and the graphics applied on are the main distinctive attributes of the balloons and they are the main cause for their complex and difficult manufacturing. The envelope is constructed from gores made of polyamide or polyester fabric, reinforced with sewn-in load tape. The gores, which extend from the base of the envelope to the crown, comprise of a number of smaller tiles connected together with the seams. Balloons' envelopes can be divided into various types with similar shape and differences only in a graphics design and special shapes, which are unique. The envelope is important as it not only defines the shape and appearance of the hot air balloons but also their flight characteristics.

The envelope shape is typically constructed in a 3D/CAD software. However, what the balloon industry needs is not only a 3D simulation of the shape but rather fine design of the "flat" 2D patterns which can be used in the manufacturing process. Flattening is often not too difficult in case of basic shapes; however, special balloon types, which can have very complex shape and whose envelope is difficult to flatten, became recently very popular. While the 3D model represents the inflated uptight shape of the balloon, after flattening to the cut design plane its shape and some parameters could be little different. In general, the most important parameters are the lengths of the separated tile edges, whole tile patch circumference, and shape of the patch.

This paper addresses an approach leading into a design of the suitable 2D shape from a given 3D surface by using a combination of flattening techniques to simulate the process of creating a 2D form. It also describes methods which are used during this process, an overview of its advantages and disadvantages and results comparison to some related works.

1.1 Related work

Research in surface flattening area has been active for many years already, therefore, many methods have been designed with various parameters and usability features. First known class of methods are the parametrization methods which are based on a bijective mapping between the original mesh and the planar mesh – the flattened surface. These methods use mostly numerical methods and linear equations system. In our work, we are not using this class of methods. An excelent survey of recent parametrization methods is given in [Wang05], see also the references therein.

Second class of methods is formed from the methods based on minimization of a strain-energy in the 2D flattened pattern. After the projection onto the plane, the length differences are measured and treated as a strain energy and some iterative method is then applied to minimize this strain energy. Several methods exist and differ in the way the energy minimization is performed; however, they have the energy minimization scheme applied on the 2D patterns in common. McCartney et al. [McCart99] proposed a flattening of a triangulated surface by minimizing the strain energy in the 2D pattern. Wang et al. [Wang02] improves this method by using a simple spring-mass system. More details about strain-energy minimization methods can be found in [Wang05].

Woven fabric related models can be considered another class of methods. Woven fabrics consist of a series of crossed vertical and horizontal threads. In [Aono94] three basic assumptions were stated; (1) the strength of the threads is usually very high, threads are inextensible, (2) thread segment between adjacent crossings is straight on the surface, and (3) no slippage occurs at a crossing during fabric deformation. These methods generally rely on physical properties of the fabric and try to approximate it; equidistant points are mapped on the original surface under predefined direction. The main problem of this class of methods is that the resulting plane pattern depends on the selected position and direction of the base line. More details about this class of methods can be found in [Wang05].

Our previous work [Kub10] was based on a simple surface planar projection followed by the woven fabric model application that finetuned this projection. This method depended heavily on the early surface projection and it inclined to incorrect results in case of complex or strongly curved surfaces. This paper proposes an improved flattening method based on a combination of the woven fabric model approximation algorithm described in [Wang05], the strain-energy minimization method used in [Wang02], and the energy releasing spring-mass system as a refinement part of the flattening process.

2 FLATENNING PROCESS

An input of the flattening process is the 3D design of the envelope surface divided into several tile meshes M_x. In our case, it is designed using Rhinoceros 3D software. This design has pre-defined locations of the seams and tiles and also the fabric yarns orientation. The main constraint, comparing to other similar tasks is that it is not possible to create any new seams neither insert any darts. It is necessary to flatten given tile as it is or detect if it can not be flattened within a given accuracy limits and it needs to be redesigned.

```
Find planar mesh approximation Γ of 3D input mesh M
while steps < max_steps do
    for node in Γ do
        CalculateForceAndDerivative()
    UpdateParticlesPositions()
    UpdateEnergy()
    if success metrics fulfilled then
        break
```

Algorithm 1: Pseudo-code of the fine tuning algorithm.

The proposed model assumes an orthotropic material, which is used where the elastic performance is sensitive to the grain direction with respect to two orthogonal axes: warp and weft. The actual input 3D surface representation is a polygon mesh; the quality of this underlying mesh is important to the success of the flattening process. Polygon mesh is created for each envelope tile, a quality of the tiling is critical for suitable result.

The flattening process itself consists of several steps applied sequentially. The first step is finding a tile mesh M planar mesh approximation Γ which is accurate as most as possible. This goal could be achieved in many various ways, we use a slightly modified woven mesh fitting algorithm described in [Wang05] in detail.

2.1 Fine tuning process

Obtained mesh grid Γ is just a tile shape approximation and it needs to be refined in a fine tuning process which is a next step of the flattening process. We propose a particles spring-mass system simulation in combination with numerical methods and Hook's law. Approximated mesh Γ is given as an input of this simulation, where mesh nodes represent masses and the links between them represent springs. In this paper, we use an energy model; planar triangular spring-mass system to obtain the refined flattening result, inspired by the [Wang02]. Thus, the process of flattening is a deformation process driven by the energy function of the spring-mass particle system.

To simulate the dynamics of mesh grid, we integrate the system of differential equations over a time. At each time step $t_{i+1} = t_i + \Delta t$ we sum all of the forces acting on each node. Force is calculated for every mesh spring using equations

$$\vec{F}_x = -(K_{weft} \cdot (l - l_0).x + K_d \cdot \Delta v.x \cdot \vec{x}) \cdot \vec{x} \qquad (1)$$

$$\vec{F}_y = -(K_{warp} \cdot (l - l_0).y + K_d \cdot \Delta v.y \cdot \vec{y}) \cdot \vec{y}, \qquad (2)$$

where l_0 is a spring rest length, K_{weft}, respectively K_{warp} are weft and warp direction parameters calculated from physical fabric properties in combination with length difference. A dumping factor K_d takes into account in the velocity calculation. Standard Newtonian equations of motion and a midpoint method are used to advance the current velocity and position over the each time step. This method has advantages in a faster convergency and its stability. With using a small derivative step, we can get reliable method which produces precise results. We will focus in our future work on an adaptive derivative step which can make the iterative process more precisely. This solution system needs to be stable and it should not let the grid to deform or the calculation stuck. However, if some spring has a length error out of the bounds, a system may become unstable and such behaviour needs to be detected and corrected immediately.

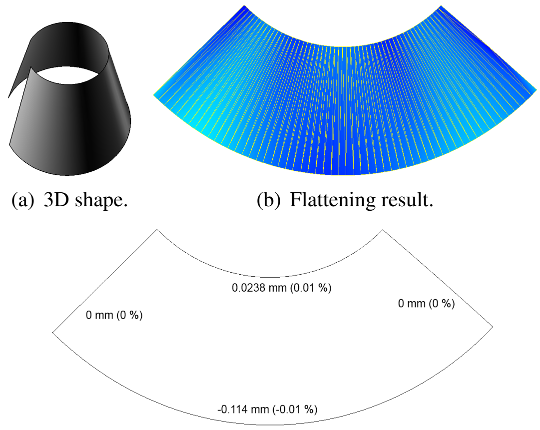
2.2 Definition of a success metric

Three accuracy criteria are used to evaluate the accuracy of the flattening process resulting surface. All of them are used as a termination criteria for the flattening finalization procedure. **Area accuracy.** Should not exceed 1 % difference between the original surface area and the flattening process resulting mesh area. However, this also depends on a complexity of the surface, more complex surfaces may have bigger are difference due to less precise result. **Shape accuracy.** We can distinguish between two types of the shape accuracy. The accuracy of each edge length and the difference between the total edge length on the M and on the Γ. A required accuracy is the difference of up to 1 mm over 1 m of length (0.1 %). However, this could be violated in case the length difference of a matching edge of an adjacent tile and overpassed edge already fulfil required accuracy. **Energy accuracy.** The most important accuracy criteria is the mass-spring system energy minimization meaning, in fact, proper overall shape. During each step of iteration, the mass-spring system energy is calculated. This value is then compared with the one of the previous step of iteration. If the energy stops decreasing or the difference between last two steps is smaller than selected treshold value of an allowed minimal energy step, the iteration process is stopped.

Area and shape accuracies are used just only as an additional metric of success and they are checked right after a completion of the flattening process. Only if the energy minimization criteria is fulfilled, these other two metrics are checked. The area and shape metrics are used to simplify a result evaluation, minimization itself would be very difficult to implement due to its complexity. The main decision is whether the tile is manufacturable and if so, result is the proper shape of the cut. If not, the balloon design should be changed.

3 EXPERIMENTS AND RESULTS

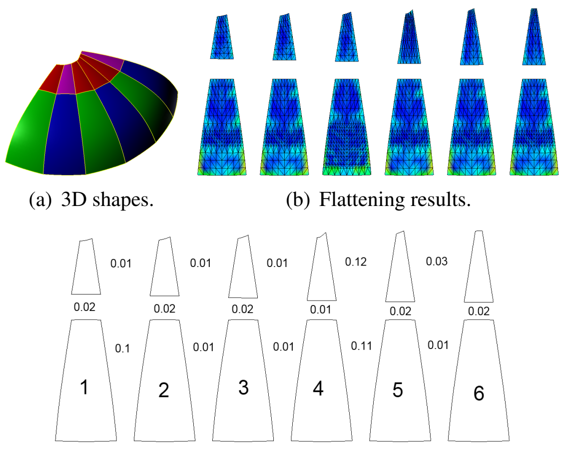
Figures 1, 2 and Table 1 show results of performed experiments with tiles which are close to developable surfaces or easy to flatten. Figures 3, 4 and Table 2 show results of experiments with complex and not developable surfaces. The order of the figures top to down: 3D shapes of panels, flattening results, and a comparison of the edges (or adjacent edges if possible) accuracy. Red colour in the flattening results image means the highest error out of acceptable bounds, blue means the smallest or no error. For tables, values in italics are stated for comparison with the other methods; however, the input data is not the same, it is only similar, so the results are not very well comparable. Minimal energy criterium was set to the same threshold value for each experiment, it is not necessary to state it.



(a) 3D shape. (b) Flattening result.

(c) Edges accuracy (in *mm*).

Figure 1: Developable surface - a cone.



(a) 3D shapes. (b) Flattening results.

(c) Adjacent edges accuracy (in *mm*).

Figure 2: Examples of well developable surfaces.

The performed experiments prove that the implemented fine tuning algorithm is very well usable for the various shapes of tiles and it is the mostly limited by an application internal meshing process. Currently, the physical properties of the fabric are not still fully implemented in the flattening algorithm; we expect result improvements of this aspect in the future work.

Tile	Area err. (%)	Shape err. (%)
Cone	**0.07**	**0.0055**
Cone [Wang02]	*0.092*	*0.174*
Cone [Wang05]	*0.25*	*0.05*
Figure 2 (bottom 1, 5, 6)	0.00	-0.01
Figure 2 (bottom 2, 3, 4)	-0.01	0.04
Figure 2 (top 5)	0.00	0.03

Table 1: Flattening results of quite well developable surfaces.

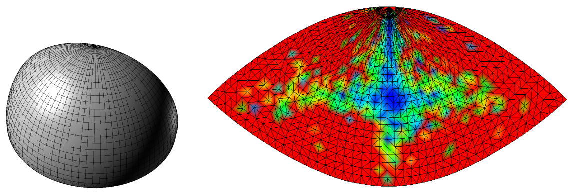
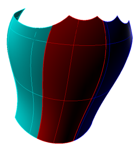
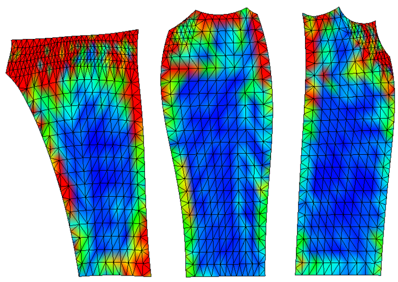


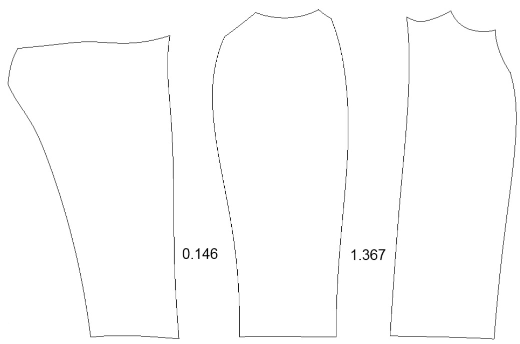
Figure 3: Example of quarter of sphere flattening. The result is unacceptable and the tile must be further subdivided.



(a) 3D shapes.



(b) Flattening results.



(c) Adjacent edges accuracy (in *mm*).

Figure 4: Examples of non easily developable complex surfaces.

4 CONCLUSION

The presented work focuses automatic flattening algorithm of hot air balloon envelopes, mostly its flatten shape fine tuning. We implemened a numerical model useful for solving the given flattening problem – a combination of a woven mesh fitting, particle system solving, and numerical methods application, and we also defined the success metric which the results of flattening problem needs to meet. The input of the presented algorithm is the previously designed 3D envelope model divided into several tiles and the result is the cut design of flattened tiles. After we apply the presented algorithm on all of the balloon envelope tiles, we receive the whole envelope cut design, where all problems caused by wrong envelope design and/or tile division can be simply detected.

Tile	Area err. (%)	Shape err. (%)
Quarter of sphere	1.93	14.01
Figure 3 left	0.87	0.19
Figure 3 middle	0.08	0.17
Figure 3 right	0.18	0.30
Garment [Wang05]	*0.30*	*1.79*
Garment [Wang05]	*0.25*	*0.05*

Table 2: Flattening results of non easily developable complex surfaces.

The results obtained by the automated process are promising. They generally differ from the ones obtained actually "by hand" and they were evaluated as having the same or better quality. Also, they are much faster and easier to obtain. The proposed algorithm is currently used in the manufacturing process and the results are being compared to the previous manufacturing processes. In our future work, we will focus on a better handling of the physical properties of fabric in proposed algorithm and on the more precision of the refinement results mainly.

5 ACKNOWLEDGMENTS

We thank to Kubicek Balloons company for technical advisement and providing data; thanks to their courtesy we were able to use their balloon designs in our research. This work has been supported by the research projects TE01010415 (V3C – Visual Computing Competence Center) and IT4Innovations (MSMT, ED1.1.00/02.0070).

6 REFERENCES

[Aono94] Aono M., Breen D.E., Wozny M.J. Fitting a woven-cloth model to a curved surface: mapping algorithms. Computer-Aided Design 26, pp.278-292, 1994.

[Kub10] Kubicek, R., and Zemcik, P. Balloon Cut Layout Based on 3D Balloon Model, in Proceedings of the IADIS CGVCVIP 2010, Freiburg im Breissgau, DE, IADIS, pp.57-64, 2010.

[McCart99] McCartney J, Hinds B.K., Seow B.L. The flattening of triangulated surfaces incorporating darts and gussets. Computer-Aided Design 31, pp.249-260, 1999.

[Wang02] Wang, C.C.L., Smith, S.S-F., and Yuen, M.M.F. Surface flattening based on energy model. Computer-Aided Design 37, pp.823-833, 2002.

[Wang05] Wang, C.C.L., Tang, K., and Yeung, B.M.L. Freeform surface flattening based on fitting a woven mesh model. Computer-Aided Design 37, pp.799-814, 2005.