

# A Film Balloon Design System Integrated with Shell Element Simulation

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## Abstract

*CAD systems that have user-friendly interfaces for assisting ordinary people to design objects is becoming common. Most of these systems combine a sketch interface with physical simulation. In this paper, we propose a system for designing balloons made of non-stretchy material such as aluminum foil, plastic film and paper. We implemented the system by using a finite element method that is based on discrete Kirchhoff triangle (DKT) shell elements and a sketch interface that enables users to easily design the realistic shape of an inflated balloon. The 2D pattern for the balloon design is generated automatically by our system. We evaluated our system by a user study with six elementary school children and their parents. These users designed target objects and responded to a questionnaire.*

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [COMPUTER GRAPHICS]: Computational Geometry and Object Modeling—Physically based modeling

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## 1. Introduction

Three-dimensional computer-aided design (3D CAD) systems are now used widely in product design. In addition, computer-aided engineering (CAE) systems are becoming common. As a result, in recent years, the study of user interfaces that target inexperienced users has become popular. At the same time, the costs for making real 3D objects from 3D CAD data are decreasing due to the spread of rapid prototyping systems such as 3D printers. However, it is sometimes difficult to realize the target shape for objects made of thin materials. These materials are used in products such as balloons or stuffed animal toys, which are made by stitching 2D material. In this case, the designer has to design 2D patterns for the target 3D shape. Because it is a type of inverse design problem, much experience and intuition are needed. In addition, it can require trial and error processes that increase the cost due to the extra consumption of materials. Although we can reduce this cost by using a computer-aided engineering (CAE) system that can analyze the behavior of products, it is still difficult to introduce the system into the field of casual design, such as do-it-yourself (DIY) projects. Most current CAD and CAE systems operate independently of each other,

and it is difficult to make them work together. This means that if we design an object with a CAD system, first we have to design the patterns with CAD and then import the data to the CAE system. Although we can see the result of balloon inflation by running a simulation in CAE, we would need to return to the CAD system if we are not satisfied with the result. To reduce the time and cost, we propose a system that enables users to design the 3D shape of a balloon directly. We believe that a balloon is a reasonable target as one of case studies for combining CAD and CAE. The proposed system automatically generates the 2D patterns for the 3D shape by running a physical simulation in the background. We assume that the target balloon is made of non-stretchy material such as aluminum, plastic film, or paper because it is not straightforward to obtain the 2D pattern from the 3D shape. Furthermore, simulating the inflation of the balloon requires precise simulation because we assume that the material is non-stretchy. The finite element method (FEM) for the physical simulation is a feature of this system.

In this paper, we describe the algorithm of the simulation, the user interface, and present a user study to evaluate our system.

## 2. Related work

The technology of computer graphics (CG) was first used to generate images or movies, not to design an actual object shape. However, it is not unusual to combine a physical simulation with a geometrical modeling system today to generate realistic CG animation. For example, sketch based modeling systems [AD06] and [Ern] include the physical simulation. Popović developed a system in which the user can directly control the result of a solid body physical simulation [PSE\*00]. These systems are intended to assist users in CG animation, not the design of a physical object.

However, in recent years some researchers have been developing systems that can design actual objects easily by using the technologies of computer graphics and user interfaces. Mitani developed a system for generating patterns for papercraft by approximating a given triangular mesh model with a set of triangle strips [MS04]. A system that automatically generates the relief from a 3D model was developed by Weyrich [WDB\*07]. Mori developed a system that generates patterns for stuffed animal toys [MI06]. These systems have the same purpose, which is to enable inexperienced users to design actual objects with a computer. Mori's study is especially similar to ours in that experimental subjects design a shape made with thin materials and then the system generates 2D patterns automatically from the user-designed 3D shape. The difference is that Mori's system uses a spring-mass simulation but our system uses FEM analysis with discrete Kirchhoff triangle (DKT) shell elements, which are used in industrial CAE systems to simulate thin and non-stretchy materials, which require precise calculations. The effectiveness of the simulation using DKT shell elements for various lamina elements was shown by Batoz in numeric experiments [BBH80].

## 3. Overview of the proposed system

First, we describe the target object of our system. The object is a balloon made with aluminum foil, a thin film material with little retractility; that is, material that is more rigid than rubber. To simplify our example, we make a balloon by gluing the border of two same-shaped patterns together (Fig. 1). Even though the structure of the balloon is very simple, it is not easy to predict the inflated shape from the pattern. The inverse is also true: it is difficult to estimate the shape of patterns from the inflated 3D shape.

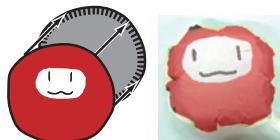


Figure 1: An example of the balloon targeted with this system.

In our system, the user inputs the projected 2D image of the inflated balloon. When the user draws the image, the pattern and the three-dimensional computer graphics (3DCG) model of the inflated balloon are generated automatically. The pattern is generated so that the inflated shape matches the image drawn by the user. Because the balloon is made with two patterns of the same shape, the system generates only one pattern. Generation of the pattern and inflated 3DCG model is performed every time the user changes the projected 2D image of the balloon. Consequently, the user can edit the shape of the balloon interactively by seeing the inflated 3D shape and the 2D pattern.

To generate the pattern, the system uses the outline of the image drawn by the user as the initial pattern. Because the inflated shape from the initial pattern often differs from the user's intended shape, the pattern can be modified so that the inflated (simulated) shape more closely resembles the drawn image (details are described in Sec 3.4). The flow of the design process with our system is as follows:

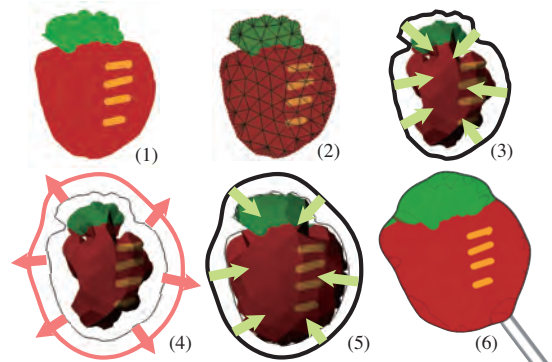


Figure 2: Flow of our system.

1. A user draws a projected image of the inflated balloon on the screen by using a mouse or pen tablet.
2. A closed loop of the silhouette is extracted from the drawn image. The system triangulates it with Delaunay triangulation.
3. The system generates the inflated 3D shape from the pattern by FEM analysis with DKT shell elements.
4. The silhouette of the inflated 3D shape and the drawn image are compared. Then the pattern is modified according to the difference between them.
5. Return to (3.).
6. When the final pattern is generated, a representation of the air intake is added.

### 3.1. Simulation

We implemented the FEM analysis with the DKT shell elements (Kirchhoff hypothesis conducts that a continuous condition is necessary for thin shell, but entirely  $C^1$  condition is very complex. Dhatt [Dha69] proposed an element that has

$C^1$  condition on discrete point in the element. It is called discrete kirchhoff triangle (DKT) element). The strain energy  $U$  of a linear thin material is described as follows:

$$U = \frac{1}{2} \int_{\Omega} \kappa D_b \kappa d\Omega \quad (1)$$

where  $E$  is Young's modulus,  $\nu$  is Poisson's ratio, and  $t$  is the thickness of the board.  $D_b$  is calculated as follows:

$$D_b = \frac{Et^3}{12(1-\nu^2)} \begin{bmatrix} 1 & & & & & \\ & 1 & & & & \\ & & 1 & & & \\ & & & & & \\ & & & & & \\ & & & & & (1-\nu)/2 \end{bmatrix} \quad (2)$$

We analyze only one side of the balloon, under the condition that the outline of the pattern does not move in the vertical direction for the simulation because of its symmetry property. Pressure is added in the direction normal to a triangular element. We used an implicit method for the analysis because of its stability, and the Newmark- $\beta$  algorithm for temporal integration. To solve the simultaneous linear equations, the conjugate gradient method is used for preprocessing the imperfect ILU resolution with ordering by the minimum degree method.

### 3.2. Mesh reuse for FEM

Our system uses the Delaunay triangulation algorithm to generate the mesh for FEM simulation. In theory, the mesh is regenerated according to the changes of the target shape. However, because this mesh generation consumes much computational time, we can omit the remeshing operations and reuse the previous mesh as long as none of the following conditions are true:

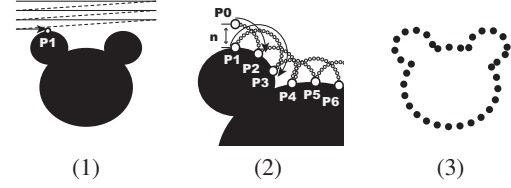
- The topology (connectivity) of the mesh needs to be changed according to the Delaunay triangulation algorithm.
- One or more triangles is reversed.
- When  $R \times 15 < L$ , where  $R$  is the radius of the inscribed circle of a triangle, and  $L$  is the length of the longest edge of the triangle.

With this simplification, we realize a fast simulation.

### 3.3. Paint interface and extraction of outline

The painted texture and outline are extracted from the shape drawn by the user. To extract the outline, which is a closed loop with no self intersections, we trace the boundary of the shape. The algorithm of this tracing is as follows. First, we define an initial position ( $P_1$ ) of the boundary by scanning horizontally from the upper left to the lower right (Fig. 3(1)). We set  $P_0 = (P_{1x}, P_{1y} + n)$ . Then we trace the boundary by scanning pixels on a circle with radius  $n$  and center  $P_i$  in

a clockwise direction to find  $P_{i+1}$  (Fig. 3(2)). Finally, we obtain the closed loop by repeating the previous operation until  $|P_i - P_1| < n$  (Fig. 3(3)). In our implementation, we set  $n = 10$  pixels.



**Figure 3:** Extracting the closed outline loop. (1) Defining the initial position. (2) Repeated tracing of the next positions. (3) The traced positions forming the final image.

### 3.4. Modification of the pattern

The goal of our system is to generate patterns of a balloon conforming to the shape drawn by the user. If we simply inflate the initial patterns (the same shape as the drawn image), the result will not be suitable; in particular, the result tends to be small. Hence, we have to modify the initial patterns so that the inflated shape matches the drawn image. To realize this, our system modifies the patterns according to the difference between the shape drawn by the user and the inflated (simulated) shape. The flow of this operation is as follows:

1. Extract the outline from the image drawn by the user. This is used as the initial shape of the pattern.
2. Triangulate the closed region with Delaunay triangulation and run the FEM simulation to produce the inflated shape.
3. Translate the coordinates  $L'$  of the silhouette of the inflated shape so that the barycenter matches the barycenter of the coordinates  $L$  of the outline extracted from the drawn image.
4. Apply the least squares method to rotate  $L'$  so that the difference from  $L$  becomes the smallest.
5. Obtain the difference vector  $v_i$ , which is  $L_i - L'_i$ .
6. Shorten  $v_i$  if the length exceeds the threshold (we set 3 mm).
7. Add  $-v_i$  to the previous coordinate of each vertex of the pattern.
8. Apply the Laplace smoothing operation to the outline of the pattern to smooth the pattern.
9. Return to (3.)

(6.) and (8.) are applied for easier simulation convergence.

### 3.5. Creation of actual balloon

The balloon, our target object, inflates by applying pressure from inside to outside, so an air intake is required. We developed our system to add the air intake to the pattern automatically. The site is a thin rectangle which has a 10 mm

inner width. The direction of the rectangle is set so that it matches the direction from the center of the pattern to the farthest coordinate on the outline.

After printing the pattern on the real material, the user glues the two patterns at the specified lines together manually, and inserts a straw into the air-intake spot. Then user blows through the straw to inflate the balloon.

#### 4. User study



Figure 4: Photo of the workshop.

We held a workshop as a user study to evaluate our system. The subjects were 6 pairs of schoolchildren and their parents. Figure 4 shows the user study. The objects shown in Fig. 5 are the balloons created by the subjects. We used sheets of tracing paper as the material.

We distributed questionnaires after the workshop. Most of the answers for the question “Was the system easy to use?” were Yes, and we received comments such as “Viewing the simulated shape is fun,” “The 3DCG looks real and it is good for viewing the shape from different angles,” and “I could see the possibilities using computers.” Moreover, almost all of the schoolchildren gave the highest score for the question “Could you draw the picture that you imaged?” In the workshop we prepared tablet PCs, so it seems that even the children could easily carry out the drawing operation.

The comment “I wanted advices or software support to show the shapes that would be inflated well” was given for the result that the shape did not inflate well in the simulation when the shape was long and included a thin section.

#### 5. Conclusions and future work

We developed a system for designing the shape of a balloon made with thin and non-stretchy material. By using FEM analysis with TDK elements, the inflated shape can be simulated. We evaluated the usability of our system by organizing a workshop. As future work, a comparison of the results with and without using our system will be conducted. We will also evaluate the computing time. This will help ascertain the most appropriate mesh for the simulation. In addition, we want to develop this system so that it can process more



Figure 5: Examples created in the workshop. Left col.: created objects, Center col.: images designed by the subjects, Right col.: patterns generated by our system.

complicated balloons made with multiple pieces of patterns. Moreover, many materials, such as other aluminum foils and polyvinyl, will be input as the thin film material for the balloon. Finally, we want to enable the use of various materials so that the user can easily specify the physical properties that are best suited to the object.

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