Interactive Furniture Design:

Using Deformable Models to Create Chairs

by

Aseem Agarwala
MIT Media Laboratory
20 Ames Street
Cambridge MA 02139
aseem@mit.edu

Submitted to the Department of Electrical Enginering
and Computer Science in Fulfillment of the
Advanced Undergraduate Project

Supervised by Mathew Brand, MIT Media Laboratory

Abstract

Deformable models that evolve under a set of mutual forces and constraints can be used to solve various problems in graphical design. We describe a system that takes as input the silhouette of a seated person and creates a chair that is aesthetically pleasing and structurally sound. We encode the input image and knowledge of furniture design into a set of force fields and constraints, and then allow several deformable models to evolve into stable shapes in this environment. The interface of the system allows the user to define the desired dimensions of the chair and affect its aesthetic outcome by changing certain constants. The result is a system that designs chairs that match the profile of the user and his/her aesthetic taste.

1.0 Introduction

Dynamic, elastically deformable contour models that evolve under appropriate constraints and forces can be used to solve many problems in vision and graphic design. These models take the form of two-dimensional meshes which operate and evolve into a stable configuration in a three-dimensional space. This work is based on the active contour splines, termed snakes, used by Kass, Witkin, and Terzopoulos to solve a variety of vision problems including edge detection, motion tracking, and stereo matching [1].

The system described in this paper uses deformable models to solve a furniture design problem. The system takes as input an image of the silhouette of a seated person, and then designs a chair that is comfortable and fits the specific back profile of the person. The software couples knowledge of the form of a chair as well as the input of the user. The user interface is an interactive three-dimensional graphics simulation of the evolution of the chair. The user can affect the chair by changing certain parameters and constants that constrain its shape. The chair is modeled as a deformable mesh.

A deformable mesh is a dynamic sheet of points that define a surface in a three-dimensional space. The points in the sheet move and evolve in three dimensions in response to a set of mutual forces and constraints. We encode the parameters of a design problem into a set of governing force equations and then subject a deformable model to these forces. Equilibrium states reached by the model may be considered solutions to the design problem. This approach to design has been used to solve various problems including free-form shape modelling of product shells [2].

Each point in the deformable mesh is subject to two different types of forces, intrinsic and extrinsic. This terminology of forces was coined by Terzopoulos in his use of deformable models to achieve 3D object reconstruction from 2D images [3]. Intrinsic forces model the mesh as an elastic physical body. They subject the mesh to a property natural to all solid surfaces, surface coherence. This is accomplished by placing attractive forces between each point and its immediate neighbor. Each point has a spring between itself and it's upper, lower, left, and right neighbors. These forces keep the mesh smooth and coherent.

The extrinsic forces result from the input image of an object profile. An object profile, also known as an occluding contour, is defined as the outline of the image region covered by the object's projection. This image is converted into a 2D potential field, where each pixel is a assigned a vector force corresponding to the gradient of the greyscale image at that point. By subjecting the deformable meshes to these forces, we constrain the mesh to match the 2D profile of the image.

This model of deformable meshes can be used to solve many problems in graphical design. The next section describes the specifics of our system and the application of deformable model to furniture design.

2.0 System Specifics

The system creates a chair in several stages. The first stage, which at present must be done by the user, is the creation and preparation of the input image. Next, the user uses a mouse to define the initial shape of the chair. The chair then evolves to match the profile of the image under constraints and constants that can be modified by the user. Finally, the base and back of the chair is created and evolved into a final form that is constrained by aesthetic and structural considerations. This chronology can be seen in figure 1.

FIGURE 1. The process of designing a chair.

The software is coded in IvySCM [4], an interpreter for the scheme language [5] with additional bindings for Open Inventor. Open Inventor is a toolkit for creating interactive 3D graphics programs on graphics workstations. Thus, the system allows the user to see the chair in 3D both during its evolution and in it's final form.

2.1 Image Preparation

The system takes as input a greyscale image in the pgm format that depicts the profile of a person in a seated position. The body of the person should be black, and the rest of the image white. The image must be blurred slightly to create a gradient field (most image packages include a blurring filter that can be used to prepare an image as input to our system). Convolution with a large kernel is desirable because it spreads information more effectively, whereas sharp, local gradients perturb the system faster than it can move to equilibrium. The image used for the design of the chairs that follow is shown in figure 2.

The image of the field is then converted into a potential field of forces that correspond to the greyscale gradient. The pgm format encodes images as a matrix Img(r,c) of greyscale values, with 255 representing white and 0 black. $Img(0, 0)$ is the upper left point in the image. Our algorithm creates a vector field $\overrightarrow{Img}(r, c)$ where each cell is a 2D vector in x, y space that represents the negative of the greyscale gradient. This creates repulsive forces along the outline of the profile in the image.

FIGURE 2. Input image.

2.2 Sitting Surface

The front of the chair is modeled as a deformable mesh that is subject to spring, image, and contour forces. This mesh is represented both as a matrix of 3D points and as a 3D model in Open Inventor. The system starts by displaying the input image on a 2D screen in a 3D space. The user then uses the mouse to select starting points for the top, middle and end of the initial surface. The y value of the top of the chair and the x value of the bottom remain constant throughout the chair's evolution. Thus, the user defines the height of the back and the length of the chair bottom when selecting initial conditions.

Once the initial surface is defined it is superimposed on the image, and then shown as it evolves towards the back of the image profile. The system iteratively recalculates positions and forces, causing the surface to deform in accordance with shape, smoothness, and image field constraints. There are several constraints that operate along with the spring and image field forces that encode knowledge of what makes a chair practical and comfortable. The chair should be symmetric about its bilateral axis, so we force this condition by only evolving half the chair, and then creating the other half by projecting the mirror image of the first half across the bilateral axis. Also, the contour of the chair in the z direction should fit a standard ergonomic curve that provides good lumbar support. This desired curve can be seen in figure 3. To achieve this, we apply contour forces to the mesh that push the chair into this curve. The angles $\theta(c)$ which represent the angle each point on this curve makes with the z-axis is calculated, and during the evolution of the chair each point is subjected to contour forces that try to push the point in a direction such its current back angle $\phi(c-1)$ and current forward angle $\phi(c)$ match the desired angles, $\theta(c-1)$ and $\theta(c)$.

Another constraint involves the smoothness of the chair lines. Along the bilateral axis of the chair which rests against the human spine we want the chair to match the profile of the human as close as possible. However, for aesthetic considerations we want the left and right edges of the chair to be as regular in its curvature as possible, despite the human profile. To achieve this, we weight the upper and lower spring forces between adjacent points to be stronger near the edge of the chair, and weak near the axis. Greater spring forces improve smoothness and regularity in the side profile.

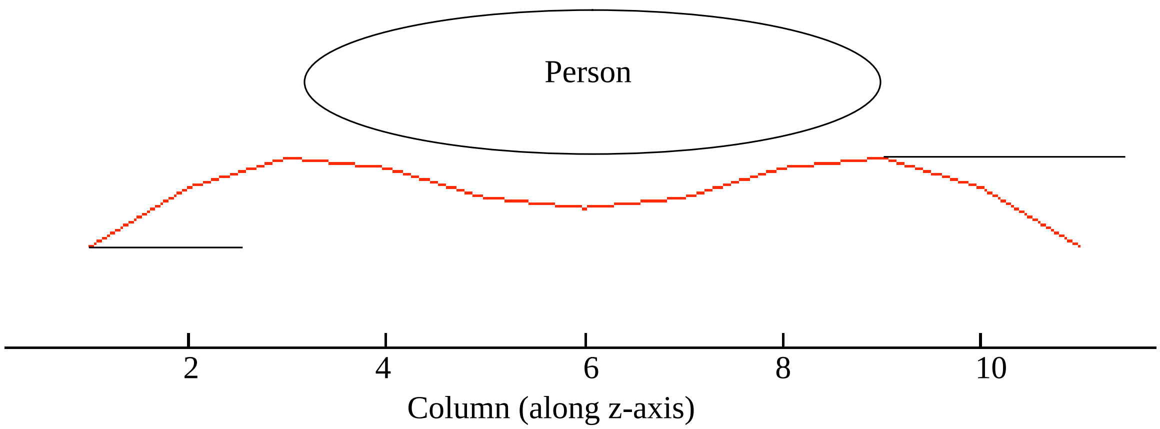

FIGURE 3. Desired contour of chair.

The algorithm uses this set of forces and constraints to calculate for each iteration a new position for each point in the mesh. After around 100 iterations a stable configuration is generally reached. The governing calculations are below. The mesh is a matrix $\vec{\beta}(\mathrm{row}, \mathrm{col})$ of 3D vectors representing a point in space. The columns span the width of the chair, and the rows span the length.

For each r and c such that:

$$-(maxC) \le c \le maxC \qquad \text{(EQ 1)}$$

$$0 \le r \le maxR \qquad \text{(EQ 2)}$$

We calculate,

$$\gamma = \eta \cdot \varepsilon \cdot (|c| + 1) \quad \text{(EQ 3)}$$

$$\overrightarrow{left} = \varepsilon \cdot (\vec{\beta}(r, c-1) - \vec{\beta}(r, c)) \quad \text{(EQ 4)}$$

$$\overrightarrow{right} = \varepsilon \cdot (\vec{\beta}(r, c+1) - \vec{\beta}(r, c)) \quad \text{(EQ 5)}$$

$$\overrightarrow{upper} = \gamma \cdot (\vec{\beta}(r+1, c) - \vec{\beta}(r, c)) \quad \text{(EQ 6)}$$

$$\overrightarrow{lower} = \gamma \cdot (\vec{\beta}(r-1, c) - \vec{\beta}(r, c)) \quad \text{(EQ 7)}$$

$$\overrightarrow{forw\theta} = \varphi \cdot \left(\theta(c) - \operatorname{atan}\left(\frac{x_c - x_{c+1}}{z_{c+1} - z_c}\right)\right) \quad \text{(EQ 8)}$$

$$\overrightarrow{back\theta} = \varphi \cdot \left(\operatorname{atan}\left(\frac{x_{c-1} - x_c}{z_c - z_{c-1}}\right) - \theta(c)\right) \quad \text{(EQ 9)}$$

$$\begin{aligned}\vec{\beta}'(r, c) = {} & \vec{\beta}(r, c) + \overrightarrow{left} + \overrightarrow{right} + \overrightarrow{upper} + \overrightarrow{lower} \\ & + \overrightarrow{forw\theta} + \overrightarrow{back\theta} + \overrightarrow{Img}(r, c)\end{aligned} \quad \text{(EQ 10)}$$

where $\vec{\beta}'(r, c)$ is the new value of the point at row r and column c, ε is a constant that weights the spring forces, and φ is a constant weighting the strength of the contour forces. The $\overrightarrow{left}$, $\overrightarrow{right}$, $\overrightarrow{upper}$, and $\overrightarrow{lower}$ spring forces enforce surface coherence. The $\overrightarrow{forw\theta}$ and $\overrightarrow{back\theta}$ contour forces calculate the present angles of the countour of the chair, and push the contour in a direction such that these angles are equal to the desired angles in figure 3. In order to make the edges smoother, γ is calculated as a function of c, ε, and the constant η such that it is larger near the edges of the chair and weak in the middle at column 0. The new position of the mesh point is then calculated by adding the forces and the present position of the point.

By applying the above set of equations through enough iterations we can achieve a stable configuration of a chair profile that satisfies the constraints specified. The results can be seen in figure 4. The user is allowed to changed the value of the constants within reasonable limits, and then see the results of those changes on the appearance and structure of the chair.

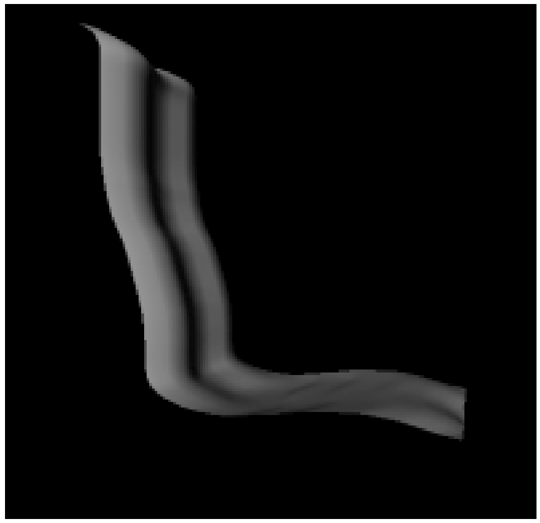

FIGURE 4. Chair surface

2.3 Chair Base

The next step in creating a chair is the design of the base. The base should be aesthetically pleasing and should use a minimum of material. Also, the base is of structural importance, and must satisfy certain constraints so that the chair is balanced and structurally sound.

In order to achieve maximum structural balance the center of the base should be directly under the center of gravity of the seated person. To calculate this point, the algorithm averages the x value of every point in the image that is above a certain threshold of darkness. While sitting, the lower legs are not supported by the floor, so points beneath the bottom of the seat are not considered. The chair should remain standing even if a person is not seated in it, so we calculate the center of gravity of the chair alone, and constrain the bottom of the base to cover that point. The last piece of information we need from the input image is the bottom of the person's feet. The base of the chair is constrained to reach to this level.

It is also necessary to decide where the base ends and the back of the chair begins. We want this row of the chair to be a hinge point, so that the seated person can tilt back slightly in his seat. To calculate this point we choose the row in the chair where the maximum curvature occurs. This is the natural break between the back and bottom of the chair.

Once this data is calculated we can create the initial base of the chair. It is represented as a deformable cylinder and is constrained so that it does not intersect the chair surface above it or itself. The top edge of the base must follow the outline of the chair exactly up to the end of the base, so we calculate this row of points and force it to remain constant. The bottom edge of the base is a circle that is centered at the center of gravity of the person, and at least wide enough to cover the center of gravity of the chair standing alone. The user can widen the bottom of the base, but outside of this intervention the last row remains constant. The middle rows of the initial base is a cylinder centered at the center of gravity of the person. This initial base can be seen in figure 5.

FIGURE 5. Initial chair base.

The deformable mesh of the base is then allowed to evolve into its final form. The only forces involved are spring forces, which cause the base to tighten around the center of gravity as much as possible while still maintaining the fixed position of the top and bottom rows. The material used to form the base is minimized by tightening the base around its axis as much as possible while still satisfying structural constraints. We experimented with adding some more complicated forces to constrain the base to follow certain mathematical curves, but we found the most pleasing results to follow from the simple model of just spring forces alone. The results can be seen in figure 6.

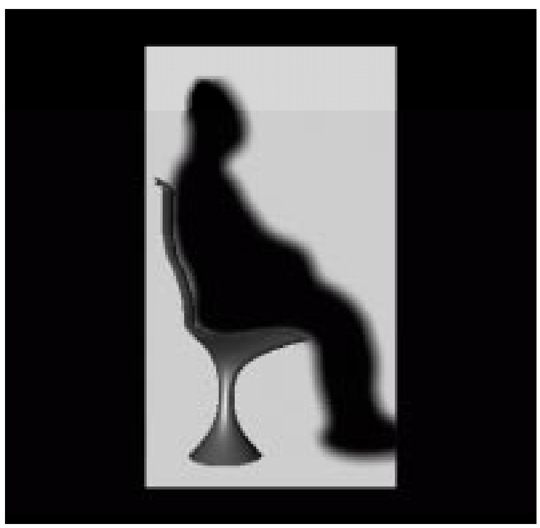

FIGURE 6. Finished Chair Base

2.4 Chair Back

The last component of our chair is the back surface. The entire outer edge of the chair back is already defined, in that it must connect with the edges of the chair surface. The bottom of the back is connected to the chair surface several rows above the row of maximum curvature that defines the end of the base. This space allows a chair to tilt back slightly.

The inner points of the chair back are not defined, however, and must be aesthically shaped. We want the back to bulge out slightly around its bilateral axis, and the surface should be smooth and maintain a convex shape. To accomplish this we model the back as a deformable mesh whose endpoints are defined by the edge of the chair surface. We create very strong spring forces, and add an additional force that encourages a slight curvature in the form of a flattened sine curve from 0 to π. Several profiles of the results of the finished chair with a back and a blue cloth pattern texture mapped across the chair surface can be seen in figures 7, 8, 9, and 10.

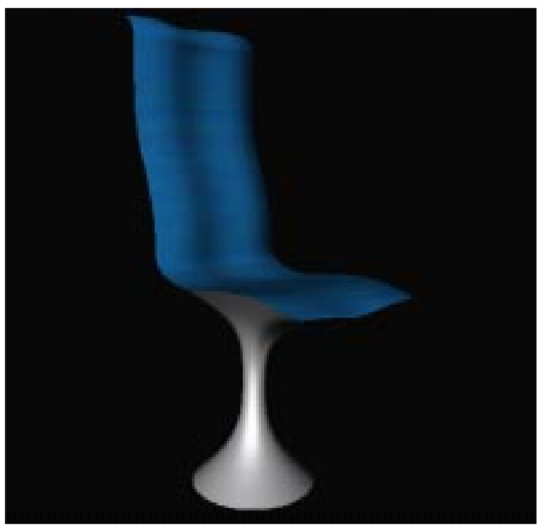

FIGURE 7. Front profile of the finished chair.

FIGURE 8. Side profile of the finished chair.

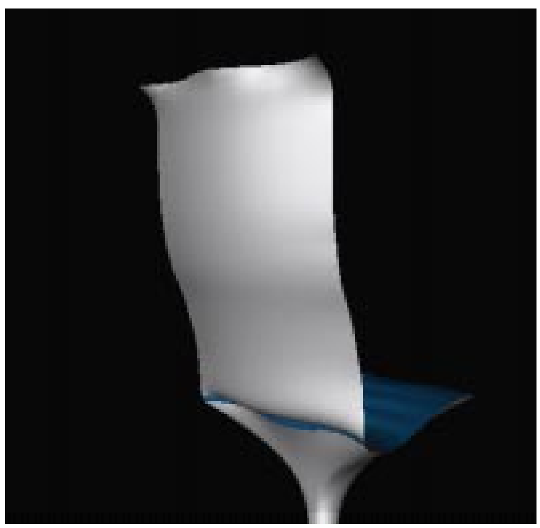

FIGURE 9. Back of the finished chair.

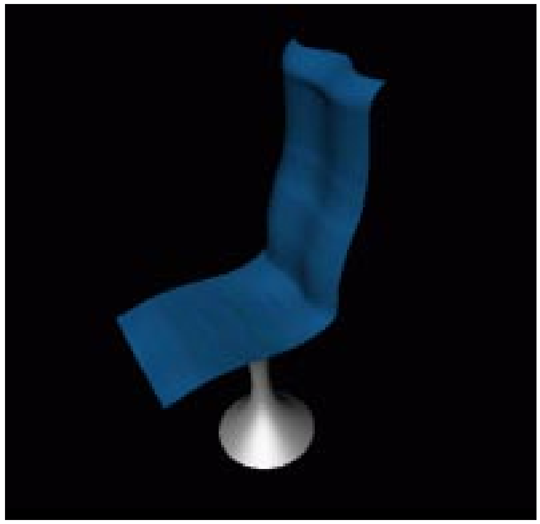

FIGURE 10. Finished chair.

3.0 Discussion

The interactive furniture design system here outlined is a simple application of a very powerful tool for solving design problems. By encoding the parameters and desires of a specific problem into a series of constraints and forces and then applying them to deformable models we can approximate a simple solution to an obtuse problem.

The chairs produced by our system are structurally sound and aesthetically pleasing. They conform to the body and provide support to the soft areas of the back.

The next step may be to find a way to fabricate them from the data. In the future, it may be possible to set up a studio where a person can sit, have a picture taken, and then have his/her profile extracted from the image using background differencing. The software could then apply a blur filter to the image itself, and proceed with the design of a custom-fitted chair. The finished chair data could be forwarded to a manafacturing process which would create a custom chair for the client.

REFERENCES

1. Kass, M.., Witkin, A., and Terzopoulos, D., Snakes: Active Contour Models, *International Journal of Computer Vision* **1** 1987.

2. Celniker, G., ShapeWright: Finite-Element based Free-Form Shape Design, Ph.D. thesis, Department of Mechanical Engineering, MIT, 1990.

3. Terzopoulos, D., Witkin, A., Kass, M., Constraints on Deformable Models: Recovering 3D Shape and Nonrigid Motion, *Artificial Intelligence* **36** 1988.

4. Russel, K., Ivy: A Scheme Binding for OpenInventor http://www.media.mit.edu/~kbrussel/Ivy.

5. Clinger, W., Rees, J., Editors, Revised(4) Report on the Algorithmic Language Scheme, *ACM Lisp Pointers* **4** 1991.