Dressing Animated Synthetic Actors with Complex Deformable Clothes

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Abstract

This paper discusses the use of physics-based models for animating clothes on synthetic actors in motion. In our approach, cloth pieces are first designed with polygonal panels in two dimensions, and are then seamed and attached to the actor's body in three dimensions. After the clothes are created, physical properties are simulated and then clothes are animated according to the actor's motion in a physical environment. We describe the physical models we use and then address several problems we encountered. We examine how to constrain the elements of deformable objects which are either seamed together or attached to rigid moving objects. We also describe a new approach to the problem of handling collisions among the cloth elements themselves, or between a cloth element and a rigid object like the human body. Finally, we discuss how to reduce the number of parameters for improving the interface between the animator and the physics-based model.

Keywords and phrases:

cloth animation, garment design, discretization, dynamic constraints, collision responses, deformable surface model

1. Introduction

In recent years, several models [17,15,7,6,1,5,1 1] have been proposed to animate deformable and soft objects such as rubber, paper, cloth, and so on. However, no complete methodology has been proposed to perform cloth modelling and animation for the complex case of synthetic actors [9].

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From our experience, we find that it is relatively easy [10] to use the elastic surface model to animate some simple-shaped objects. Flags, tablecloths, scarves, carpets and skirts (as shown in Fig.1), all of which consist of one or two surface panels, have few constraints. But it is somewhat difficult to realistically animate complex objects consisting of many surface panels like trousers or jackets without proper dynamic constraints. Problems include seaming the surface panels together, attaching them to other rigid objects, and calculating collision responses when cloth self-collides or collides with a rigid object. Some algorithms of collision response were described [7,13] but they are not effective in cloth animation except for special cases such as a single skirt.

Figure 1. A simple cloth: only the skirt is deformable and designed as a single panel.

In our approach, we work as a tailor does, designing garments from individual two-dimensional panels seamed together. The resulting garments are worn by and attached to the synthetic actors. When the actors are moving or walking in a physical environment, cloth animation is performed with the internal elastic force and the external forces of gravity, wind, and collision response.

In this paper, Section 2 explains the physics-based model used for the simulation of cloth motion. Section 3 describes the collision response algorithm. Section 4 discusses the algorithm of joining and attaching elements of the deformable panels. Finally in Section 5, we discuss how to reduce the number of parameters and how to choose values which provide realism and mathematical stability, thus improving the interface between the animator and the physics-based model.

2. The dynamic model

Our work is based on the fundamental equation of motion as described by Terzopoulos et al. [15] with the damping term replaced by a more accurate one proposed by Platt et al. [14]:

$$\rho(\mathbf{a})\frac{d^2\mathbf{r}}{dt^2}+\frac{\delta}{\delta \mathbf{r}}\iint_{\Omega}\|\boldsymbol{E}\|^2 da_1\, da_2+\frac{\delta}{\delta \mathbf{v}}\iint_{\Omega}\|\dot{\boldsymbol{E}}\|^2 da_1\, da_2$$

$$+\frac{\delta}{\delta \mathbf{r}}\iint_{\Omega}\|\boldsymbol{B}-\boldsymbol{B}_0\|^2 da_1\, da_2 = \Sigma\, \mathbf{F}_{ex} \qquad (1)$$

Because this equation is quite similar to Eq.1 of [15], we discuss only the modified third term and refer the reader to [15] for notation and explanations.

In the second term of Eq.1, $\boldsymbol{E} = \boldsymbol{G} - \boldsymbol{G}^o$ is called the Lagrangian strain tensor. In the third one, $\dot{\boldsymbol{E}}$ is the time rate of $\boldsymbol{E}$ and is defined as [14]:

$$\dot{\boldsymbol{E}}_{ij}(\mathbf{r}(\mathbf{a}))=\frac{d}{dt}\boldsymbol{E}_{ij}=\frac{1}{2}\dot{G}_{ij}=\frac{\partial \mathbf{r}}{\partial a_i}\cdot\frac{\partial \mathbf{v}}{\partial a_j}+\frac{\partial \mathbf{r}}{\partial a_j}\cdot\frac{\partial \mathbf{v}}{\partial a_i} \qquad (2)$$

This term works like a dissipative function. We choose to replace it because the one used in [15] is scalar. So, no matter where energy comes from, it will be dissipated. For example, gravitational energy is dissipated, resulting in a surface which achieves a limiting speed and is not continually accelerated. In our case, we use Raleigh's dissipative function [4] generalized for a continuum surface [14]. As $\boldsymbol{E}$ is the strain (a measure of the amount of deformation), $d\boldsymbol{E}/dt$ is the "speed" at which the deformation occurs. This means that the surface integral may be considered a rate of energy dissipation due to internal friction. This implies that the variational derivative with respect to velocity of the surface integral will minimize the "speed" of the deformation. With this approach, no dissipation occurs when the surface undergoes rigid body displacement like when falling in an air-free gravity field. This improves the realism of motion.

Taking the variational derivative in Eq.1 and keeping only terms of the first order, expression Eq.15 of [15] becomes, with the new dissipative function,

$$f_{in}=\sum_{i,j=1}^{2}-\frac{\partial}{\partial a_i}\{((\alpha_{ij}+\gamma_{ij})\frac{\partial \mathbf{r}}{\partial a_j}\}+\frac{\partial^2}{\partial a_i \partial a_j}(\beta_{ij}\frac{\partial^2 \mathbf{r}}{\partial a_i \partial a_j}) \qquad (3)$$

This expression gives the internal forces — due to stretching, dissipation and bending — that act on an infinitesimal part of the surface located at $\mathbf{r}$. In this expression, we define:

$$\alpha_{ij} = \eta_{ij}\,(G_{ij} - G^0_{ij}) \qquad (4a)$$

$$\gamma_{ij} = \varphi_{ij}\,(\dot{E}_{ij}) \qquad (4b)$$

$$\beta_{ij} = \xi_{ij}\,(B_{ij} - B^0_{ij}) \qquad (4c)$$

which are constitutive functions of the elastic properties of the material.

In Eq.4, G_{ij} and B_{ij} can be computed with the help of their definitions given in Eq.3 and Eq.4 of [15] respectively. $\dot{E}ij$ can be computed as in Eq.2 above. And η_{ij}, φ_{ij} and ξ_{ij} are physical constants which can be computed as shown later.

On the right side of Eq.1, we put all external forces. Contact forces coming from collisions with the cloth itself or any rigid object like an actor's body are described in the next section.

In reality, complex clothes or garments usually consist of many fabric panels. To apply the elastic deformable surface model, the polygonal panel should be discretized using the finite difference approximation method. The discretization of the cloth boundary follows the technique in [15].

3. Collision response

This problem is handled in two steps. The first one is collision detection. This means that we have to find any object's triangle (including those belonging to the cloth itself) within a threshold distance from cloth's vertices. Several algorithms have already been proposed [7, 16, 13]. When a collision is detected, we pass through the second step where we act on the vertices to actually avoid the collision. This may be done using a potential field method as suggested by Terzopoulos et al. [15]. A detailed algorithm is described by Lafleur et al. [7] for Marilyn's skirt in the film *Flashback* [8]. Although the method works, the use of this type of force is somewhat artificial and cannot provide realistic simulation with complex clothes. In fact, the effect degrades when the potential becomes very strong, looking like a "kick" given to the cloth. To improve realism, we propose the use of the law of conservation of momentum for perfectly inelastic bodies. This means that kinetic energy is dissipated, avoiding the bouncing effect.

Case 1: Self collision

We use a dynamic inverse procedure to simulate a perfectly inelastic collision. Such collisions between two particles are characterized by the fact that their speed after they collide equals the speed of their centers of mass before they collide.

Let p_o be a point from one part of the cloth that collides with a triangle on another part. Let p_1 be the point where the collision occurs on that triangle. All physical quantities at p_1 are obtained by linear interpolation from values at the triangle's vertices. Let us call $\mathbf{u}_i$ and $\mathbf{v}_i$ the speed before and after the collision where i stands for 0 and 1. $\mathbf{F}_i$ will be the resultant of external and internal forces at i and $\mathbf{f}_{u_i}$ is an unknown force which, when added to $\mathbf{F}_i$ makes $\mathbf{v}_i$ equal $\mathbf{V}_C$, the speed of the centers of mass of particles 0 and 1 before they collide.

Assuming that forces are constant in the time interval, speed after the encounter will be

$$\mathbf{v}_0 = \mathbf{u}_0 + \frac{(\mathbf{F}_0 + \mathbf{f}_{u_0})\,\Delta t}{m_0} \qquad (5)$$

With $$\mathbf{V}_c = \frac{m_0\,\mathbf{u}_0 + m_1\,\mathbf{u}_1}{m_0 + m_1} \qquad (6)$$

and the soft collision criteria

$$\mathbf{v}_0 - \mathbf{V}_c = 0 \qquad (7)$$

we find for $\mathbf{f}_{u_0}$:

$$\mathbf{f}_{u_0} = \frac{m_0 m_1 (\mathbf{u}_1 - \mathbf{u}_0)}{(m_0 + m_1)\,\Delta t} - \mathbf{F}_0 \qquad (8)$$

Adding $\mathbf{f}_{u_0}$ at $\mathbf{F}_0$ and proceding similarly while replacing 0 by 1 and 1 by 0 in Eq.5, Eq.7 and Eq.8 will make the interaction perfectly inelastic.

Case 2: Collision between cloth and human body

In this case, to simulate perfectly inelastic collision, we cancel out the velocity and force components of p_0 that lie along the outward normal vector located at p_1. Now p_1 belongs to a triangle which composes a rigid object. Again physical quantities are interpolated from their values at the triangle's vertices.

Let us define the speed of p_0 relative to p_1. Then we have:

$$\mathbf{v} = \mathbf{v}_0 - \mathbf{v}_1 \qquad (9)$$

$$\mathbf{v}_{//} = (\mathbf{v} \cdot \mathbf{n}_1)\,\mathbf{n}_1 \qquad (10)$$

$$\mathbf{v}_{\perp} = \mathbf{v} - \mathbf{v}_{//} \qquad (11)$$

which are the components of $\mathbf{v}$ both along and perpendicular to $\mathbf{n}_1$, respectively. Then to cancel out speed, we add $-\mathbf{v}_{//}$ to $\mathbf{v}_0$ if the dot product between $\mathbf{v}_{//}$ and $\mathbf{d} = \mathbf{r}_1 - \mathbf{r}_0$ is positive.

For forces, we apply a similar procedure. Let

$$\mathbf{f}_{//} = (\mathbf{F}_0 \cdot \mathbf{n})\,\mathbf{n} \qquad (12)$$

$$\mathbf{f}_{\perp} = \mathbf{F}_0 - \mathbf{f}_{//} \qquad (13)$$

which are the components of $\mathbf{F}_0$ both along and perpendicular to $\mathbf{n}_1$, respectively. But before cancelling out $\mathbf{f}_{//}$ from $\mathbf{F}_0$, we can add a frictional force:

$$\mathbf{f}_f = -\mu \left|\mathbf{f}_{//}\right| \frac{\mathbf{v}_{\perp}}{\left|\mathbf{v}_{\perp}\right|} \quad \text{if} \quad \frac{\mu\left|\mathbf{f}_{//}\right|}{m\left|\mathbf{v}_{\perp}\right|}\Delta t \leq 1$$

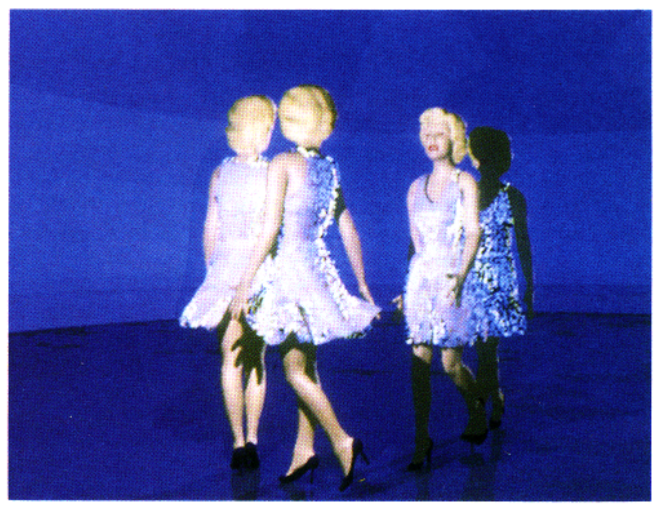
$$\mathbf{f}_f = -m\frac{\mathbf{v}_{\perp}}{\Delta t} \quad \text{else} \qquad (14)$$

where μ is a frictional constant characteristic of the interaction. The first condition ensures that $\mathbf{f}_f$ will prevent an increase of speed in the inverse direction. If the frictional force is too high, the second value is taken and makes $\mathbf{f}_{\perp}$ go to zero. Adding $\mathbf{f}_f$ and $\mathbf{f}_{//}$ to $\mathbf{F}_0$ when the dot product between $\mathbf{f}_{//}$ and $\mathbf{d}$ is positive and $-\mathbf{v}_{//}$ to $\mathbf{v}_0$ when the dot product between $\mathbf{v}_{//}$ and $\mathbf{d}$ is positive makes certain that p_0 and p_1 are never forced together when p_1 belongs to a heavy object.

4. Joining and attaching

In the animation of deformable objects which consist of many surface panels, the constraints that join different panels together and attach them to other objects are very important. In our case, two kinds of dynamic constraints [14, 2] are used during two different stages. When the deformable panels are separated, forces are applied to the elements in the panels to join them according to the seaming information. The same method is used to attach the elements of deformable objects to other rigid objects. When panels are seamed or attached, a second kind of constraint is applied which keeps a panel's sides together or fixed on objects. For example, in cloth creation and animation, all the polygonal deformable panels are designed in two dimensions. Seaming information is also indicated. The polygonal panels are then transformed into a three-dimensional space. Then according to the seams, forces are applied to the elements on the edges of the panels to put them together. The direction and magnitude of a seaming force depends on the positions of the elements, their masses, and metric factors, etc. This procedure has to be performed dynamically to let panels deform as they encounter objects like an actor's body. When the elements are close enough, their positions are forced to be the same. The panels are similarly attached to the body of a synthetic actor. After the creation of the deformable objects, another kind of dynamic constraint is used to guarantee the seaming and attaching. Fig.2a shows an example of a complex dress with many panels while a texture is applied in Fig.2b.

(a)



(b)

Figure 2. (a) Complex deformable clothes: dresses are first designed with 2D panels; the panels are placed around the model's body, then external sewing forces are applied to the seam lines indicated on the panels while the physical deformation model is processed. **(b)** Texture mapping can also be applied to the garment; in this picture, spangle texture is used.

To put together sides of panels (or a side of a panel to a rigid object), we put constraints on points belonging to sides according to the seam information recorded at the creation stage of the garment.

In the process, as long as $|\mathbf{r}_{01} - \mathbf{r}_{02}| > d$ the constraint of the first type applied

$$\mathbf{f}_i = k\eta_i m_i(\mathbf{r}_j - \mathbf{r}_i), \tag{15}$$

making the distance decrease over time.

As soon as $|\mathbf{r}_{01} - \mathbf{r}_{02}| < d$, according to the momentum law:

$$m_1\mathbf{v}_{01} + m_2.\mathbf{v}_{02} = (m_1 + m_2)\,\mathbf{v}_m \tag{16}$$

we put the second type of constraint.

$$\mathbf{v}_m = (m_1\mathbf{v}_{01} + m_2.\mathbf{v}_{02}) \,/\, (m_1 + m_2) \tag{17}$$

$$\mathbf{r}_m = \mathbf{r}_{01} + (\mathbf{r}_{02} - \mathbf{r}_{01}).m_2 \,/\, (m_1 + m_2) \tag{18}$$

Thereafter points on a seam stay together.

In formulas above, $\mathbf{r}_{0i}$, $\mathbf{v}_{0i}$, $m_{i\,(i=1,2)}$, are the position vector, velocity, and mass of element i (i =1,2) before the constraint is applied to them; $\mathbf{r}_m$, $\mathbf{v}_m$ are the position vector and velocity of both points 1 and 2 after the constraint applied to them. d is the threshold combining distance, k is a constant, and $\eta_i = \eta_{i_{11}}$ (or $\eta_{i_{22}}$ depending if point i belongs to a vertical or horizontal side) is the metric factor of the material of the panel.

In the case where point 2 belongs to a rigid object, we make the assumption that mass is infinite and no constraints are applied. In this case Eq.17 and Eq.18 comes

$$\mathbf{v}_m = \mathbf{v}_{02} \tag{19}$$

$$\mathbf{r}_m = \mathbf{r}_{02} \tag{20}$$

5. Automatically computed parameters

Physics-based animation models are very powerful because they allow the production of realistic results. Unfortunately, models are generally too complex to be used by an animator with no background in physics. For example, in the physics-based cloth model from Eq.1, quite a few parameters should be specified by the animator. Each parameter has a physical meaning and controls a physical property. To model clothes made from different kind of fabrics, we should find parameter values which make clothes move realistically. In addition, these parameters control the mathematical stability of the model, so it is not a trivial task to put them all together.

To overcome these difficulties, we propose a way of computing all the parameters from just two which have more intuitive meaning to people with no background in physics. Our goal is to introduce a few user parameters intuitive in meaning and insensitive to discretization. This technique allows testing with very few points defining a cloth, and we can look for the physical properties to be modelled with little CPU time. Then, when satisfied, we may discretize as much as we want without searching for a new set of parameters.

The first parameter to calculate is the mass for each node. But, we consider density a more fundamental quantity than mass, because it is independent of how clothing panels are discretized. The animator should select, for example a value ranging from 0.005 gr/cm^2 for silk to 1.000 gr/cm^2 for heavy leather. Mass at a node is then calculated as follows:

$$m(a) = \rho(a)da_1da_2 \tag{21}$$

The second parameter controls the resistance to stretching. To compute it, we use an artificial criterion: the percentage a clothing panel will stretch when suspended under gravity. If the norm of gravity is g and if λ is the percentage of stretch tolerance, we have:

$$\eta_{11} = mgh_v/2/\lambda/100 \tag{22a}$$

$$\eta_{22} = mgh_h/2/\lambda/100 \tag{22b}$$

$$\eta_{12} = \eta_{21} = (\eta_{11} + \eta_{22})1/2 \tag{22c}$$

In this expression, η_{ij} is a force multiplied by a squared length. For η_{12} and η_{21}, we take the mean value from η_{11} and η_{22} as it is shown in Eq.22c.

The third parameter to be calculated is Δt, used to control the step size in the numerical integration of Eq.1. Furthermore, Δt should be correlated with real-time or a video time unit. This means that in a simulation from t_1 to t_2 with a step size of Δt, we can record a video frame each $N\Delta t$ = 1/25 sec. resulting in a cloth animation sequence that is neither too fast nor too slow. We should not forget that the time parameter also controls the mathematical stability of the numerical integration of Eq.1. The lower the Δt, the greater the accuracy and stability, but the larger the processing time. The best values are then a matter of compromise.

As a clothing panel in our model may be considered a suitable medium in which waves can travel, we can find [12] that phase speed of lower node waves can be calculated as:

$$v_v = (\eta_{11}/m)^{1/2} \tag{23a}$$

$$v_h = (\eta_{22}/m)^{1/2} \tag{23b}$$

where v_v and v_h are wave speeds in the vertical and horizontal directions, respectively. A good Δt could reasonably be chosen to make a wave travel only a fraction l of the inter-vertex space in one time step:

$$\Delta t = \mathrm{min}\,(h_v/v_v,\, h_h/v_h) \,/\, l \tag{24}$$

where a good value for l is 2 or 3.

The fourth parameter is ξ_{ij}, which appears in Eq.1. This parameter controls the resistance to bending. A zero value corresponds to no resistance at all, which means a cloth moves very freely like satin. For greater values cloth appears like rigid cotton or even leather or plastic. Again, we are looking for values independent of discretization but in this case, we introduce a user parameter c that has no physical meaning for the user parameter, like η_{ij}. This value is given by

$$\xi_{11} = cmgh_v^4 \tag{25a}$$

$$\xi_{22} = cmgh_h^4 \tag{25b}$$

$$\xi_{12} = \xi_{21} = (\xi_{11} + \xi_{22})1/2 \tag{25c}$$

The fifth parameter controls the rate at which the energy coming from stretching will dissipate. The computation is analogous to the problem of a mass attached to a damped spring [12]. This means that, for the ideal case of a single mass, the movement which results from a starting position out of its rest position is of three kinds, depending on the relative amplitude of η and γ (see [2]). In our problem, the best relations between η_{ij} and γ_{ij} are:

$$\gamma_{11} = 2h_v(m\ \eta_{11})^{1/2} \tag{26a}$$

$$\gamma_{22} = 2h_h(m\ \eta_{22})^{1/2} \tag{26b}$$

$$\gamma_{12} = \gamma_{21} = (\gamma_{11} + \gamma_{22})^{1/2} \tag{26c}$$

and a stretch panel will return to its rest position without oscillation.

To summarize, parameters m, η_{ij}, Δt, ξ_{ij} and γ_{ij} are all obtained with only three input values: the density ρ the elongation percentage λ and the number c. With such an approach, all physical parameters lose their tensor meaning and become scalar. This results in an isotropic cloth model; physical properties are the same in all directions. This is not the case in real life, but we consider this a small price to pay for such simple use of physical properties. To overcome this, the animator – with free control of these parameters – can act on other directions by means of multiplicative factors.

Fig.3 shows a fashion show sequence; the walking trajectory has been given using an interactive tool dedicated to the design of walking trajectories for human figures [3]. Fig.4 shows an example of cloth animation during a motion simulated using dynamics.

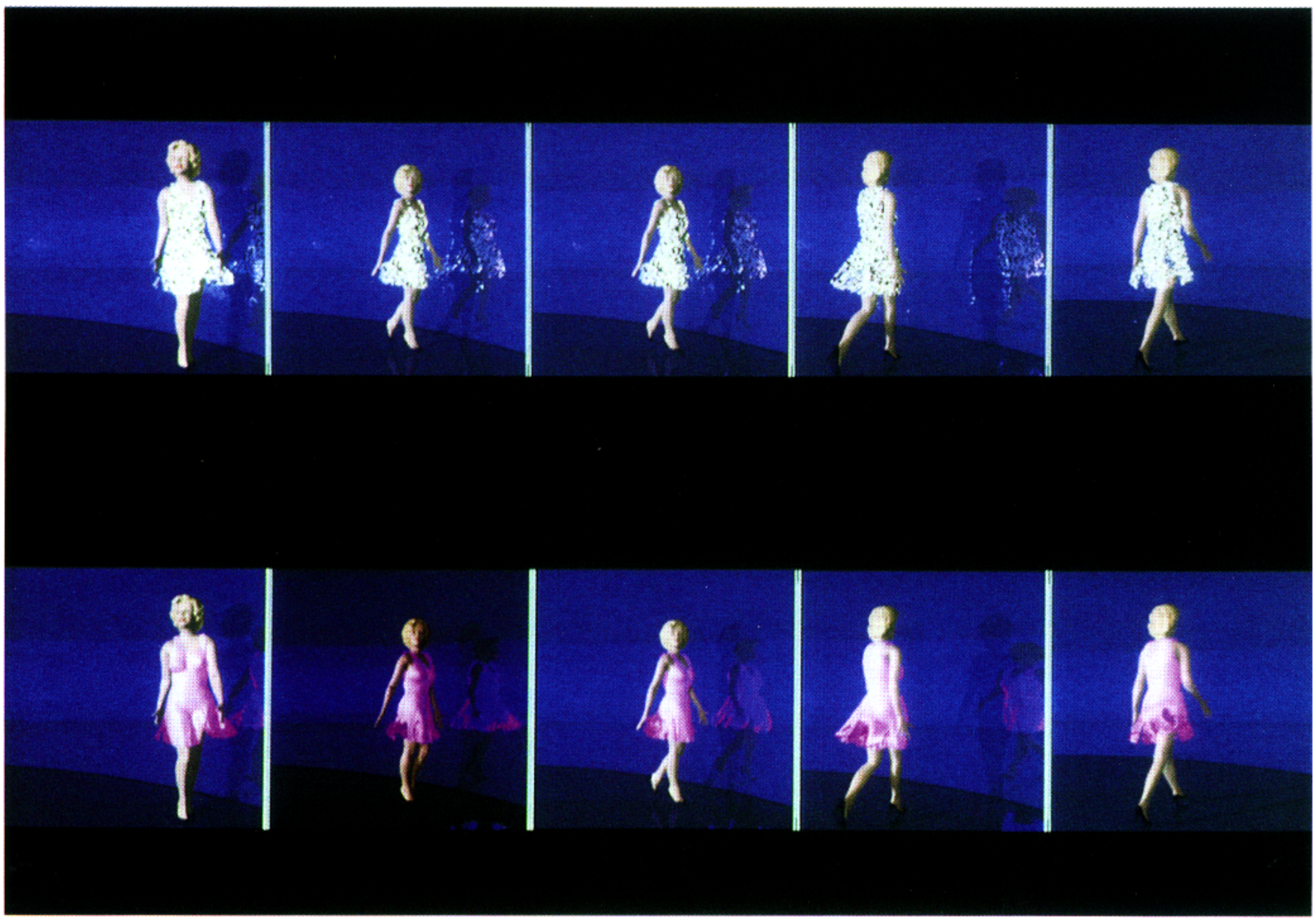


Figure 3. Fashion show sequence (film in preparation). The walking motion is performed using a global human free-walking model built from experimental data on a wide range of normalized velocities.

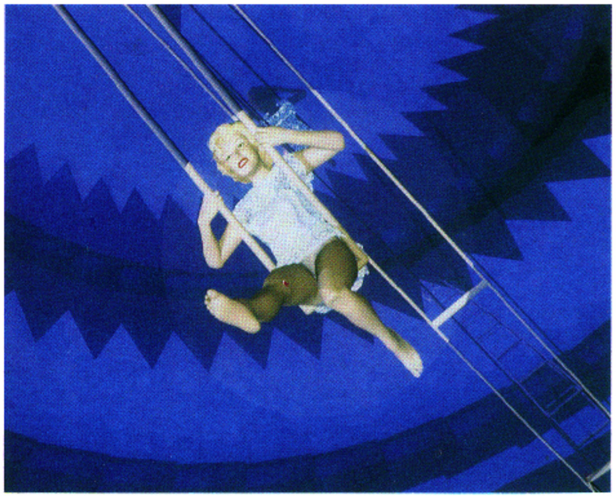


Figure 4. Marilyn as a trapezist is wearing a short 3D dress. The trapeze motion is calculated using dynamic simulation.

6. Conclusion

We have developed clothing software according to the above algorithms. First, polygonal cloth panels are interactively designed and edited in two dimensions. Then the panels are discretized in three dimensions and applied using the elastic model. Clothes are seamed and attached around the synthetic actor, and when the actor moves in space, external forces like gravity, wind, and collision responses are applied to the clothes. Clothes and garments are very complex deformable surfaces consisting of many differently shaped fabric panels joined together. Cloth modelling and animation have significant meaning in deformable object animation, and they have potential application in the garment industry. In our present research, we try to make clothes look more realistic, incorporating, for example, various textures, buttons, belts and other decorations.

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