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# Realistic Cloth Animation

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**Abstract**

*In this paper we present a model for the realistic simulation of the mechanical behavior of cloth based on the Finite Elements Method. The use of this method in a material with the elastic properties of cloth has some problems of convergence to which we propose a solution in this work.*

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Three–Dimensional Graphics and Realism]: Animation

**Keywords:** Animation, Cloth, FEM

## 1. Introduction

There can be distinguished two different types of models for cloth simulation, discrete models and continuous models.

In the discrete models cloth is represented by a set of particles with mass that are linked through energy equations, as is the case of particle systems [BHW94, EWS96, BW98], or those based on masses and springs [Pro95, VMT97, CK02, BMF03, CS04]. These models produce very good visual results, which is usually enough for some industries such as cinematography and animation, although they have some drawbacks, like:

- A simplified use of the mass distribution, leaving out dynamic considerations.
- A linear treatment of cloth properties, except in [CS04], not considering the hysteresis processes.
- A simple model for the weft of the knitted fabrics, not considering the anisotropic character of some wovens.
- There is no consideration of the singularities in the composition of garments: foldings, seams, lining fabrics, etc.
- Simulation parameters are adjusted in order to obtain the expected visual results, in spite of using values obtained in dating test.

In the fashion industry, competence has raised the necessity of tools that allow to reduce costs in the productive processes [Com03, eT05]. In this sense some solutions have been proposed for allowing a rapid prototyping in the design phase [Fas, RI05, Opt05]. For the use in the textile industry the results of garment simulation must be based in the mechanical behavior of fabrics in order to obtain results for a later analysis. There have been proposed some methods that apply physical theories considering the cloth as a continuum, the so–called continuous models.

Within this category of continuous models is framed this work, in which we apply the Finite Elements Method (FEM), highly used in diverse engineering disciplines [ZT93]. We propose solutions to the different problems that its use presents in the analysis of materials with the characteristics of clothes, such as [CK02, VMT02, CS04]: high computing times and the lack of stability of FEM when applied to thin materials supporting compression forces.

The contribution presented in this work is, on one hand, to solve the aforementioned problems and, on the other hand, to apply a more realistic physical model that allows to obtain results that can be applied in the textile industry sector, specially in the development of prototype validation tools in the fashion design sector.

Section 2 shows the main works in computer graphics related to cloth simulation using FEM. Section 3 explains the properties that have the clothes when they are considered as a continuous medium. We present a necessary introduction to FEM in section 4 to be able to understand the notation used and our contributions. In section 5 we give a solution to the problems that usually appear in cloth simulation with

FEM. Finally we present some results in section 6 and our conclusions in section 7.

## 2. Related works

The use of FEM in cloth simulation has been done basically in two fields: textile engineering and computer graphics.

In textile engineering the main purpose is the analysis of the cloth at microscopic level (fibres and wefts) [CCCS91, CG95, SL03]. These studies aim at knowing the mechanical behavior of clothes when facing external actions. In this sense the graphical simulations serve only as a visual support of the results. The most studied behavior is ”drapingt’t’.

In computer graphics, instead, a macroscopic treatment of the cloth is done. In this area, one of the first works is that of Terzopoulus et al. [TPBF87], which make a physical treatment of deformable models as a continuum. The model presented makes uses the elasticity theory and the Lagrange movement equations, evaluatee with finite differences.

Works using FEM are mainly related to behavior simulation of flexible materials and deformable solids [MMDJ01, GHDS03, MNGA04, MG04, ITF04]. Although these works could be applied to cloth simulation, they do not have a specific treatment for them.

Following, a revision of those works that have made a real use of FEM in cloth simulation in the field of computer graphics is exposed.

The first work is that of Eischen et al. [EDC96], which focuses specially on curvature starting from the experimental results of Kawabata [Kaw80], founding the displacements analysis in differential geometry. They propose a mechanism to overcome the problem of the influence that the finite elements deformation rate has in the convergence of the method. They discretize the cloth as a mesh of linear quadrilateral elements, without facing the problem of irregular meshes and the local curvature. Their results consider only the draping behavior and they do not make a nodal ponderation of the mass, neither mention the damping treatment, and for this reason the system presents a harmonic behavior.

In [TWZC99], the authors make a treatment of the non linearity of cloth elasticity, with a special consideration on the global curvature. They discretize the cloth with triangular finite elements and they simplify the model by neglecting planar deformations and focusing on the draping behavior of the cloth. They do not address the problem of buckling, neither the dynamic behavior.

In the work of [EKS03] an analysis of the cloth as a viscoelastic material is done. To our concern this is the only work that shows good visual results. They make an equitable mass distribution between all the nodes. They use linear triangular elements, which makes it not possible to compute the local curvature. Global curvature forces are calculated without the FEM. They do not establish a relation between acceleration and displacement that allows a correct analysis of the nodal damping coefficients, making use of an energy dissipation based technique.

## 3. Clothes as a continuum

Clothes have some particular properties [Hu04]:

- Anisotropy of the elastic properties, in the weft and warp directions.
- High deformation rate under relatively low loads.
- Non linear elasticity.
- Hystheresis effects in deformations.
- Reversible plasticity.
- Low compression rate.

The dynamic behavior of the clothes will be determined by the Lagrange equation particularized for the continuum [Gol50], assuming the application of non conservative forces, so:

$$\frac{\partial V(\vec{r})}{\partial \vec{r}} + \gamma\left(\frac{\partial \vec{r}}{\partial t}\right) + \mu\left(\frac{\partial^2 \vec{r}}{\partial t^2}\right) = \vec{F}_{ext} \qquad (1)$$

where $\vec{r}$ is the position vector of a point of the cloth mesh, $V(\vec{r})$ is the elastic potential, $\gamma$ is the damping density, $\mu$ is the mass density and $\vec{F}_{ext}$ are the applied external forces.

By applying the elasticity theory [LL59], the deformations produced in the cloth can be expressed in terms of the metric tensor. For the in–plane deformations:

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\delta u_i}{\delta x_j} + \frac{\delta u_j}{\delta x_i}\right) \qquad (2)$$

where $u_i$ and $u_j$ are the displacements in the cloth surface, and $\varepsilon_{ij}$ means the deformation. When $i = j$ the deformation is an elongation, whereas $i \neq j$ means a shearing. Non planar deformations are obtained by applying the curve theory [dC74], by the following expression:

$$\kappa_{ij} = \frac{\delta^2 u_i}{\delta x_i \delta x_j} \qquad (3)$$

When $i = j$ the deformation is a curvature, whereas for $i \neq j$ it is a torsion.

## 4. Finite Elements Method

The FEM allow to find the solution of a differential equations system representing a model of a physical problem in a continuous medium [ZT93].

Since equation 1 is a particular case of the variational principles [Gol50], we can apply the FEM to the cloth considered as a continuous medium.

The method can be resumed as follows:

1. Discretization of the medium in geometrical units called *finite elements*, configuring a topology (a mesh).
2. Definition of a *shape function* that represents the physical behavior of the finite elements. Shape functions are interpolation functions based on control points called nodes, and whose expression is conditioned by the geometry of the finite element type and its number of nodes. The shape function allow to approximate any dynamic magnitude of the element by the value that this magnitude has in its nodes.
3. Assembly of the equations associated to the finite elements in order to deal with the whole domain.
4. Application of the contour conditions, the initial conditions and the loads.
5. Simultaneous resolution of the equation set in order to obtain the magnitude values at the nodes.

The displacements field of a node is computed according to the following equation:

$$u = \sum_{i=1}^{n} N_i a_i \tag{4}$$

where $u$ is the displacement of any point of the element, $N_i$ is the shape function and $a_i$ is the displacement of the node $i$ of the element.

By replacing equation 4 in 2, and particularizing it for a generic node, we obtain a relation between deformations and nodal displacements associated to the in–plane deformations:

$$\begin{bmatrix} \varepsilon_{ix} \\ \varepsilon_{iy} \\ \varepsilon_{ixy} \end{bmatrix} = \begin{bmatrix} \frac{\delta N_i}{\delta x} & 0 \\ 0 & \frac{\delta N_i}{\delta y} \\ \frac{\delta N_i}{\delta y} & \frac{\delta N_i}{\delta x} \end{bmatrix} \begin{bmatrix} a_{ix} \\ a_{iy} \end{bmatrix} \tag{5}$$

where $a_{ix}$ and $a_{iy}$ are the displacements of the $i$ node.

The relation that appears in equation 5 can be expressed as $\varepsilon = B_i a_i$, where $B_i$ is called the *operator matrix*. For nodal rotations and the curvature deformation this matrix is:

$$B_i^c = \begin{bmatrix} \frac{\delta^2 N_i}{\delta x^2} + \frac{\delta^2 N_i}{\delta y^2} & 0 & 0 \\ 0 & \frac{\delta N_i}{\delta x} & 0 \\ 0 & 0 & \frac{\delta N_i}{\delta y} \end{bmatrix} \tag{6}$$

Equation 1 particularized for FEM can be expressed in a matricial manner as:

$$K \cdot U + C \cdot \dot{U} + M \cdot \ddot{U} = F_{ext} \tag{7}$$

where $K$ is the *stiffness matrix*, $U$ is the matrix containing the nodal displacements, $C$ is the *damping matrix*, $\dot{U}$ is the velocity matrix, $M$ is the *mass matrix*, $\ddot{U}$ is the acceleration matrix and $F_{ext}$ is the matrix of external forces.

Each element is associated to a local or intrinsic reference system, with $\xi$, $\eta$ and $\zeta$ components (see figure 1). The position of the nodes remains constant in the intrinsic reference system.

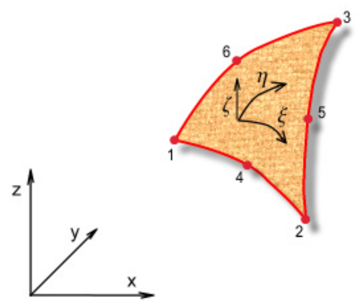


**Figure 1:** *Deformed Finite Element.*

In order to relate the local reference system with the global one (that of the system), with $\vec{e}_x$, $\vec{e}_y$ and $\vec{e}_z$ components, the *Jacobian* matrix is used:

$$J = \begin{bmatrix} \frac{\delta x}{\delta \xi} & \frac{\delta y}{\delta \xi} & \frac{\delta z}{\delta \xi} \\ \frac{\delta x}{\delta \eta} & \frac{\delta y}{\delta \eta} & \frac{\delta z}{\delta \eta} \\ \frac{\delta x}{\delta \zeta} & \frac{\delta y}{\delta \zeta} & \frac{\delta z}{\delta \zeta} \end{bmatrix}$$

where

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \sum_{i=1}^{n} N_i \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} + \sum_{i=1}^{n} N_i \frac{\zeta}{2} \vec{V}_{3i} \tag{8}$$

and where $\vec{V}_{3i}$ is a normal vector to the element particularized for node $i$.

All the matrices that participate in equation 7 are conditioned by the displacements that appear at the nodes of the elements which compose the cloth mesh. We represent these displacements in the displacements matrix:

$$U_i = \begin{bmatrix} u_i & v_i & w_i & \theta_{ix} & \theta_{iy} \end{bmatrix}^T$$

where $u_i$, $v_i$ and $w_i$ are the displacements in directions $\vec{e}_x$, $\vec{e}_y$ and $\vec{e}_z$ respectively, and $\theta_{ix}$ and $\theta_{iy}$ are the rotation angles around $\vec{e}_x$ and $\vec{e}_y$.

The velocity matrix $\dot{U}$ is made up of linear and angular velocity components. The same applies to the acceleration matrix $\ddot{U}$, with respect to the accelerations.

The stiffness matrix $K$ "contains" the material properties, through the *Young* module ($E$) and the *Poisson* coefficient ($\nu$) [LL59]. Their components are obtained according to the equation:

$$K_{ij} = \int\int B_i^T D^e B_j \Upsilon |J| d\eta d\zeta \tag{9}$$

where $D^e$ is the elasticity matrix of element $e$ which contains the nodes $i$ and $j$. $\Upsilon$ is the cloth thickness and $|J|$ is the Jacobian.

The mass matrix $M$ contains information about the inertia of the medium, whereas the damping matrix $C$ is responsible for stabilizing the system towards equilibrium positions, having their components the following expressions:

$$M_{ij} = \int\int N_i \rho^e N_j \Upsilon |J| d\eta d\zeta \tag{10}$$

$$C_{ij} = \int\int N_i \mu^e N_j \Upsilon |J| d\eta d\zeta \tag{11}$$

where $\rho^e$ is the mass density and $\mu^e$ is the damping density, associated to the element $e$ to which nodes $i$ and $j$ belong.

## 5. Proposed model

As we have already mentioned, we propose a model based on the treatment of the cloth as a continuous medium, where the dynamic is analyzed with the FEM, to which we impose some modifications in order to take into account the particular properties of the clothes.

### 5.1. Shape functions

In order to discretize the cloth dominium we apply a triangle mesh generation technique based in *Delaunay* [MTTW95]. This technique is adequate, together with the FEM, if the shapes and sizes of the triangles satisfy certain restrictions, mainly those due to the deformation adjust criteria that we shall see in section 5.5.

Each triangle represents one finite element in which vertices we put nodes that we call "main nodes". We put other three nodes at the middle point of each edge of the finite element, having thus a total of six nodes (see figure 1).

The expressions for the shape functions are:

$$\begin{aligned} N_1 &= L_1(2L_1-1) & N_2 &= 4L_1L_2 \\ N_3 &= L_2(2L_2-1) & N_4 &= 4L_2L_3 \\ N_5 &= L_3(2L_3-1) & N_6 &= 4L_3L_1 \end{aligned}$$

where $L_1 = 1-\xi-\eta$, $L_2 = \xi$ and $L_3 = \eta$.

### 5.2. Dynamics

We consider the cloth has directional isotropy, which main directions are associated to the weft and the warp [Hu04]. For this reason, the elasticity matrices that we use for computing the stiffness matrix (equation 9) are, for planar deformations:

$$D_p^e = A \begin{bmatrix} \frac{E_{tr}}{E_{ur}} & \frac{E_{tr}}{E_{ur}}\nu_{ur} & 0 \\ \frac{E_{tr}}{E_{ur}}\nu_{ur} & 1 & 0 \\ 0 & 0 & Q \end{bmatrix} \tag{12}$$

where

$$A = \frac{E_{ur}}{(1-\nu_{tr}\sqrt{s})(1+\nu_{ur}\sqrt{s})}$$

$$Q = (1-\nu_{tr}\sqrt{s})(1+\nu_{ur}\sqrt{s})$$

and where $E_{tr}$ is the Young module for the weft, $E_{ur}$ is the Young module for the warp, $\nu_{tr}$ is the Poisson coefficient for the weft and $\nu_{ur}$ is the Poisson coefficient for the warp.

The elasticity matrix for non planar deformations is:

$$D_c^e = H \begin{pmatrix} 1 & s\nu_{ur} & 0 \\ s\nu_{ur} & 1 & 0 \\ 0 & 0 & 1-\nu_{tr} \end{pmatrix} \tag{13}$$

where

$$H = \frac{E_{tr}\Upsilon^3}{12(1-\nu_{tr})(1-\nu_{ur})}$$

Since the elasticity matrix parameters ($E_{tr}$, $E_{ur}$, $\nu_{tr}$, $\nu_{ur}$) change with the cloth deformation [Kaw80], there are hysterical behaviors in the cloth, making it necessary to deal with this variation in some way. We use two and three–order exponential curves in order to give a good approximation to the hysteresis [Lah02].

We solve the instability produced by the little oscillations in the displacements, consequence of the non–harmonic characteristics of equation 7, by estimating the value of constant $\mu^e$ of equation 11 from data appearing in [Gid04]:

$$\mu^e = \alpha \frac{|K^e|}{\rho^e} \tag{14}$$

where $\alpha$ is a constant relate to the elastic properties of medium , and $|K^e|$ is the determinant of the stiffness matrix associated to the planar deformations of an element $e$.

The distribution of terms in each mass submatrix $[M_{ij}]$, in order to include the inertial terms due to the node rotations, is:

$$[M_{ij}] = \begin{bmatrix} M_{ij} & 0 & 0 & 0 & 0 \\ 0 & M_{ij} & 0 & 0 & 0 \\ 0 & 0 & M_{ij} & 0 & 0 \\ 0 & 0 & 0 & I_{jx} & 0 \\ 0 & 0 & 0 & 0 & I_{jy} \end{bmatrix}$$

where components $M_{ij}$ are the terms obtained from equation 10, and $I_{jx}$ and $I_{jy}$ are obtained from the following equations:

$$I_{jx} = \int\int M_{jj}(y_j^2 + z_j^2)\, dy\, dz$$

$$I_{jy} = \int\int M_{jj}(x_j^2 + z_j^2)\, dx\, dz$$

where $x_j$, $y_j$ and $z_j$ are the global coordinates of point $j$.

### 5.3. External forces

The external force matrix for each node is formed with the components of the total resultant force and the rotation moments caused by this force:

$$F_i = \left[F_{i_x}\, F_{i_y}\, F_{i_z}\, M_{\theta_x}\, M_{\theta_y}\right]^T$$

We distinguish two types of forces depending on the context of application in the cloth: elemental and nodal.

If the force is distributed along the whole element, elemental force $\vec{F^e}$, as is the case of air friction, we determine the contribution of this force has in the nodes with the following expression:

$$F_i = \int\int N_i \vec{F^e} \Upsilon |J| d\xi d\eta \tag{15}$$

The rotation momentums are obtained with the expression:

$$M_{\theta_i} = -\frac{E\Upsilon^3}{12}\frac{\delta u_i}{\delta x_j} \tag{16}$$

For nodal forces, the components of the total resultant force are obtained directly, and their momentums are computed according to $\vec{M_i} = \vec{r_i} \times \vec{F_i}$.

### 5.4. Curvature

The curvature deformation can be produced whether by forces located out of the cloth surface or by compression forces at the cloth surface.

In our model we distinguish between local and global curvature.

Local curvature is the one that appears at the closed surface of the finite elements, and can be measured as a consequence of the type of finite element that we use, as the shape functions are quadratics. Starting from equation 3 and particularizing it for the FEM we have:

$$\kappa_{ii} = \frac{\partial^2 N_i}{\partial x_i^2} u_i$$

which is the local curvature rate we use to evaluate the $B_i^c(1,1)$ term of the matrix from equation 6.

The global curvature appears at the connection between elements. The reaction forces of the elements that make up the curvature are forces of a global scope that we estimate from Kawabata curvature dating tests [Kaw80], throughout an extrapolation process from data obtained by simulating a 20×5 cm cloth by submitting it to the dynamic restrictions of a real cloth.

An effect known as *buckling*, that appears when compression forces are applied at the cloth surface, is the bending produced as a consequence of the non–linearity of the cloth elastic properties, and in a minor way of the trellising and the low compression rate of the cloth. In order to consider this effect we separate the forces which cause the curvature into pure bending forces and compression forces (buckling generators). To determine the compression forces we project the external forces in the plane defined by the three main nodes of the element. The damping forces are those found in this plane. Then, we check if they have broken the critical value established by the *Euler load* relation [KJL04], in order to distribute the remaining value among the nodes, introducing an almost local force that avoids the value of the deformations associated to the buckling to be big and to produce divergence in the resolution of the system. If it is not the case, the forces are coupled to the rest of forces acting upon the nodes.

### 5.5. Distortion

FEM presents some problems when it is applied to low rigidity materials, as is the case of clothes. Finite elements, under little loads, are highly deformated, thus making relevant the errors produced in the approximation and turning the system inestable and close to diverge [SL03]. There are several geometrical bounding techniques in the elements in order to avoid this "distortion" [Ede01].

We have determined empirically that the operating ranges in our models are:

- The internodal distance has to be comprised between 0.6 and 1.3 times the initial distance.
- The angle between edges has to be comprised between $30^\circ$ and $85^\circ$.

When the element breaks the limit values of internodal distance, we make the following:

1. We rectify the node positions to a non distortion situation.
2. We evaluate the displacement increment between the rectified and the distorted positions. This increment represents the displacement excess $U'$.
3. With this displacement excess we introduce internal forces according to the relation $K \cdot U' = F$, which are coupled to those the nodes already have.

In the case of distortion being due to angular excess between edges, we operate in an analogous manner but introducing moments instead of forces.

In the case of the distortion being much higher than the established limit values ($> 50\%$), we reduce the system integration time step in order to obtain more adjusted values, going back to the predefined step when we get past the time instant in which the distortion was produced in a number of applied steps.

(a) Detail of curvature with hysteresis.

(b) Cloth with a complex contour.

**Figure 2:** *Images from two animations.*

## 6. Results

In figure 2 we show two images obtained from the simulation of a poncho shaped cloth wore by a dummy with dress–up pose. The properties of woven used in both simulations are shown in table 1.

| | |
|---|---|
| woven | silk (56%)<br>poliester (44%) |
| mass density | $70\ g/m^2$ |
| $\nu_{tr}$ | 0.125 |
| $\nu_{ur}$ | 0.117 |
| $E_{tr}$ | 3657 N/m |
| $E_{ur}$ | 3267 N/m |
| thickness | 0.33 mm |

**Table 1:** *Properties of the simulated woven.*

In order to treat the collisions we distinguish between detection and reaction. The detection process is founded in the calculation of relative distances and including volumes, in a similar way as that described by Furhmann *et al.* [FSG04], but with some improvements in collisions response due to the operational versatility of FEM when evaluating the dynamic variables of any point of a given element. The detection tolerance that we use is based on a kinematic minimal distance. During the detection there appear some collisions between the cloth and the dummy (a non deformable solid), and between the cloth itself (selfcollisions).

Once the collision is detected, we operate according to the particle collision dynamic [Gol50], extrapolating the dynamic variables and the masses of the collision points from the values these magnitudes have at the nodes, following equation 4. We consider the collision to be inelastic, with a disipative energy $E_{dis} = \vartheta v_{rel}^2$, with $\vartheta$ depending on the nature of the collision (we use a value of 0.13 for selfcollisions and 0.45 for the rest), being $v_{rel}$ the relative velocity between the points that collide.

As for the integration method, we use a fourth order Runge–Kutta with adaptative time step [AP98]. The step variation is conditioned not only by the error rate which determines the integration step, but also by the adjustments made in the collision management and the control of finite elements distortion.

Simulations have been made on a PC computer with an AMD Athlon XP 2600+ processor and a 400 MHz bus, obtaining the results shown in table 2.

| Animation | a | b |
|---|---|---|
| step | 10 $\mu$s | 10 $\mu$s |
| time/frames | 14.67 s | 17.32 s |
| elements | 3325 | 4712 |
| distortions | 300 | 174 |
| bucklings | 285 | 57 |
| collisions | 200 | 391 |
| size | 1.10m$\times$1.10m | 1.10m($\phi$) |

**Table 2:** *Comparative table of the simulations.*

## 7. Conclusions

The proposed model presents the following features:

- Considers curvature deformation, whether local of global.
- Considers the directional isotropy of the cloth properties and its hysterical behaviors.
- Considers the buckling effect.
- Avoids distortions produced in the results when reaching high deformation levels.
- Considers the relation between mass and rigidity, in agreement with the damped dynamic processes.
- Considers the distribution at the nodes of the forces extended to each element.
- Allows for the discretization of clothes with complex geometry, due to the use of triangular geometry finite elements and quadratic shape functions.

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