SIACG 2002 - 1st Ibero-American Symposium on Computer Graphics
1-5 July 2002, Guimarães - Portugal

Simulating E-Garments Dressed on Personalised Avatars

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Abstract

We present a general computational architecture that solves the problem of the production of physical-based virtual textiles and garments (so called electronic garments or e-garments), applicable in Internet-based electronic-commerce scenarios. We focus in the evaluation of their visual and mechanical precision, relatively to the textile quality control procedures adopted by the industry. Our proposed architecture includes a client that authors an e-garment dressed onto a personalised avatar, establishing the boundary conditions of the mechanical system and, a server, that solves the equilibrium equations through time of such system, using optimised numerical procedures. The client inputs 2D cutting patterns from apparel CAD vendors, defines the seams between the CAD patterns, sets fabric material proprieties, loads a personalised avatar into a 3D scene, places the patterns relative to the 3D avatar, configures simulation parameters and instructs the remote server to simulate the e-garment dressing process. We conclude with the validity of our new computational framework for modelling e-garments made of plain-woven fabrics and the applicability of the system in a more global Internet-based electronic commerce solution for on-line shopping of apparel and fashion goods.

Keywords

Physical-based Modeling, Virtual Textiles, Electronic Garments, Avatars, B2C Electronic Commerce

1 Introduction[1]

Recent studies carried in the framework of European research initiatives [1], have shown that there is a growing interest in the availability of realistic virtual textiles and virtual garments dressed on "avatar" representations of humans (or virtual "twins"), on business-to-business and business-to-consumer scenarios over the Internet. Companies in the Fashion Retail sector in Europe think [2] that the provision of 3D virtual environments, populated with these virtual objects, in their Internet-based Electronic Commerce solutions, will attract more customers, improve their 'high-tech" oriented image, thus benefiting their market share, while decreasing their operational costs. Companies also think [2] that on-line fashion products shopping, providing end-users with the possibility to "try" on a new virtual clothing item, with the 3D virtual "twin" and visualise it in the virtual "catwalk", is a pleasant and attractive experience, providing more "fun" to the fashion home shopping scenario.

In the context of these R&D activities, we present a system architecture for the computation of virtual textiles and garments (e-garments), applicable in electronic-commerce solutions in the apparel and fashion products industrial sectors. This paper is specifically focused in the problem of producing virtual textiles and garments and the evaluation of their visual and mechanical precision, relatively to the Textile Material Quality Control procedures adopted by the industry. The issue of compressing and decompressing the pre-simulated motion of E-garments, stored in a file, is also tackled. Other relevant topics regarding components of a full electronic-commerce solution, such as 3D virtual environments [3], avatar generation [4], middleware and security modules, are described elsewhere. The system adopts an innovative mechanical model for fabrics, developed by the authors and described in [5, 6, 21]. This model uses the Classical Theory of Elasticity of the continuum [7], in planar tensile and bending material deformation modes and also, the theoretical framework of the mechanics of coupled particle systems. The model was largely influenced by a number of outstanding contributions from both the Textile Engineering [8, 9, 10, 11] and Computer Graphics [12, 13, 14, 15] communities.

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[1] This work was funded by the European IST 11078 project, "FashionMe, Fashion Shopping with individualised avatars".

1. CLIENT-SERVER SYSTEM ARCHITECTURE

According to the user requirements, we have developed a client-server architecture, depicted in Figure 1 and referred to as E-Fabric, that computes and visualises with high degree of precision, the dynamics of dressing personalised avatars with 3D virtual garments. We consider the hypothesis that the cutting patterns, from where garments are produced, are made of cloth whose proprieties are based on real fabric material, and are modelled as deformable surfaces seamed together over the avatar. There is a requirement for a high degree of mechanical precision and visual realism, towards industrial and electronic commerce applications of virtual textiles.

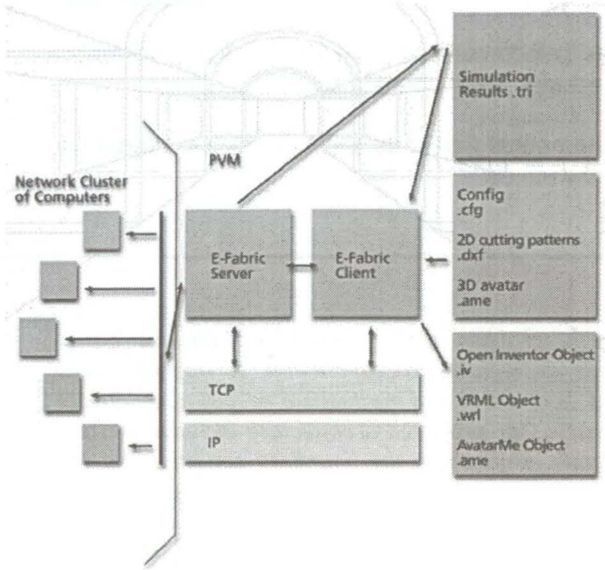

Figure 1 Client-Sever architecture of E-Fabric

Textile Quality Control experiments being currently used in the Textile and Apparel industries, related to fabric free-form deformation and drape, may be also simulated, such as tensile and bending tests, simulating Kawabata [16] and FAST [17] objective measurement systems. Other fabric free-form deformation conditions, such as draping and buckling in compression and in shear, are also supported. The application uses as its input, textile material data related to fabric deformation, 2D cutting patterns produced by Apparel CAD applications (in DXF- Drawing eXchange File format[2]) and 3D geometric avatars, produced by image-based 3D digitalisation of persons (using available AvatarMe [4] technology). In the implemented architecture, the client runs on PC-Windows platforms and the server runs either on a remote Unix machine (SGI, Linux), or on a remote Unix-based parallel architecture [22]. Open Inventor[3] and 3D Studio MAX[4] "plug-in" versions for the client have been developed by our group. The system outputs its results in the Open Inventor, VRML (Internet standard for the exchange of 3D geometrical and topological data) and proprietary 3D Studio data formats.

2. E-FABRIC CLIENT

The E-Fabric client receives from the server, a codified pre-computed physical-based simulation of electronic garment dressing or virtual fabric deformation: The client is then able to decode and visualised it, or to run a new simulation test and repeat the first step. The fabric samples can be regular (of rectangular or circular shapes), or irregular (such as cutting patterns), in interaction with life-like avatars. The tests to be configured are: (1) Electronic garment dressing simulation, with collision detection with the avatar and self-collision detection of the garment with itself, in static and dynamic environments; (2) Several fabric deformation tests: A tensile test with fabric planar deformation along any direction in respect to the warp (simulating an Instron extensometer); Fabric buckling in compression; Fabric buckling in shear; Simple or Cantilever Beam Bending, Pure Bending; Fabric draping with double bending under the gravity field.

In the pre-simulation stage (see Figure 2), the E-Fabric Authoring client starts by reading 2D cutting patterns of a garment model[5], in the DXF format, exported by Apparel specific CAD packages. As a result, a *.poly* file is obtained for each pattern, containing the definition of the polygon of its external contour. A *.seam* file is also initialised, which will later include the seaming information, topologically linking some of the patterns. The obtained polygons have vertexes irregularly distributed in the contour, which is an undesirable feature, for the required process of polygon triangularisation, for mechanical simulation purposes. To turn the contour vertexes distribution more regular, our

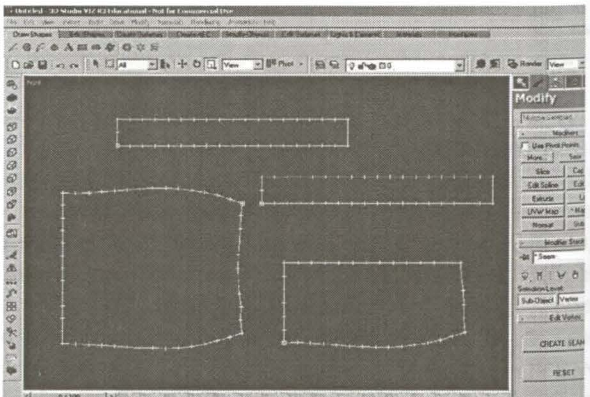

Figure 2 Imported 2D CAD patterns with regular vertex distribution

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[2] DXF is an "industry de facto" standard, from AutoDesk, used in Apparel for the exchange of geometrical and topological data of 2D cutting patterns, between CAD packages from different vendors.

[3] Open Inventor is a registered trademark of TGS.

[4] 3D Studio Max is a registered trademark of Autodesk.

[5] The CAD patterns were provided by Maconde, the largest Portuguese garment manufacturer

algorithm starts by defining the polygon sides, by following the contour vertexes until two edges create a predefined angle (30º). We then compute the length of each side and equally distribute the new points (whose number is a parameter) along that side (as we can see in Figure 2), updating accordingly the *.poly* file.

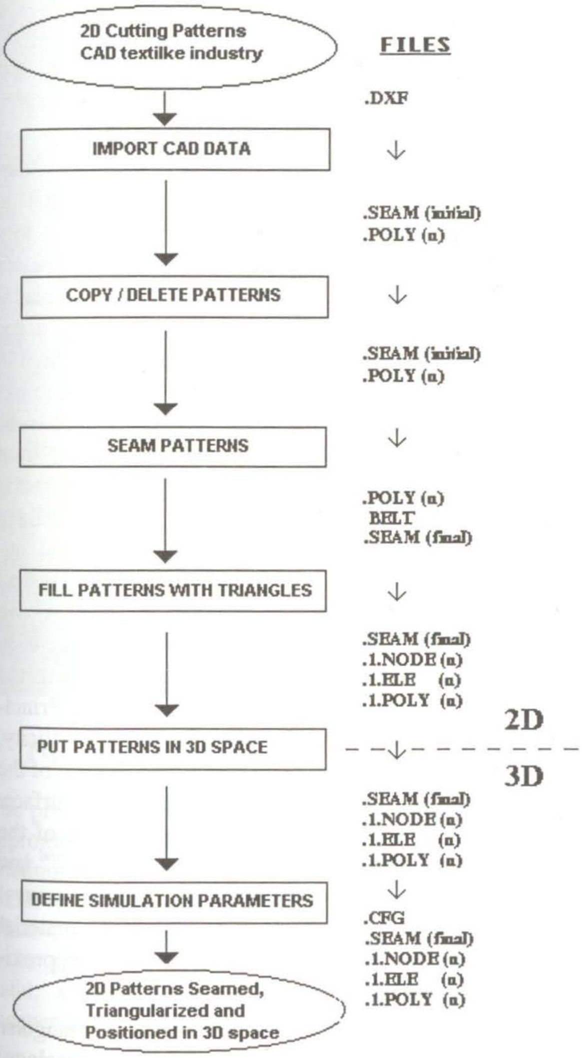

Figure 3 Process model of Pre-simulation of Electronic

To proceed with garment dressing simulation, some of the patterns may be interactively deleted (such as pockets, button holes, etc) and others copied (to create symmetric patterns, for example). We are now in the position of interactively creating the topology of the patterns to be seamed. For this, we have to perform interactive pick operations, of the same number of vertexes from two of the patterns, as depicted in Figure 3. We finalise the process by specifying the picked vertex order by which the seam is created and, as a result, the *.seam* file is produced. During simulation, the selected patterns will be dynamically joined along the picked vertexes. Some vertexes may also be selected, to define "belt or sleeve points", such that, during mechanical simulation and upon colliding contact between these "belt or sleeve points" and the avatar, these ones remain adjusted to the avatar surface, with zero velocity.

Another important aspect of this pre-simulation stage, is the triangularisation of regular or irregular cutting patterns, which are then subjected to the application of dynamic boundary conditions. This process is produced according to the notation and data formats of the public domain *Triangle* program [19], which performs Delaunay triangularisation. This program handles 2D polygonal shapes, concave or convex, with or without holes. The triangularisation of each of such objects, ensures that the contour vertexes are not modified relatively to the *.poly* file, and creates the following data structure:

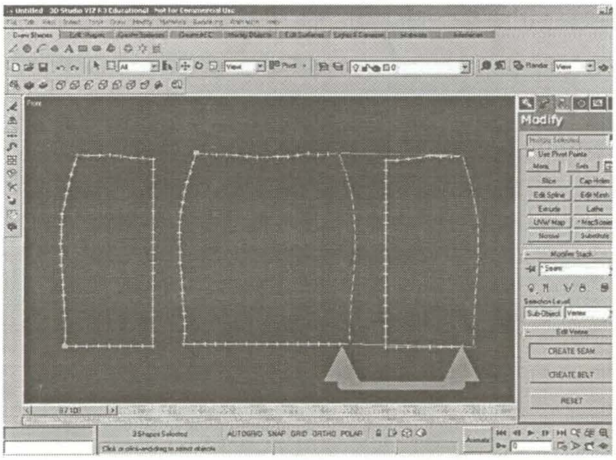

Figure 4 Interactively creating topoligical seams between 2D CAD patterns.

- a list of all vertexes (or particle positions) of the shape interior and exterior contour (*.1.node* file),

- the list of all triangles of the shape (*.1.ele* file),

- the list of external edges (*.1.poly* file), including specific attributes of each edge, enforcing, for example "belt or sleeve" type of boundary conditions.

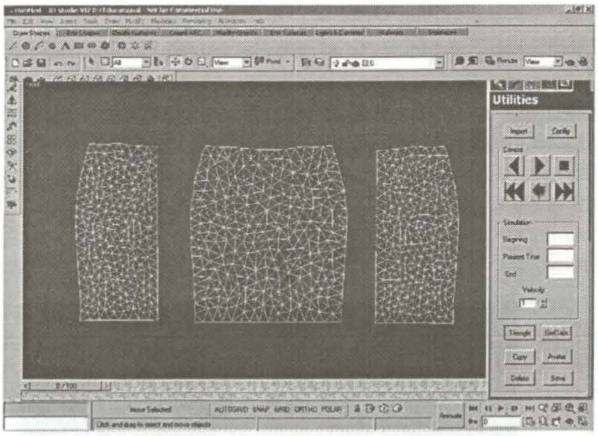

Figure 5 Filling the interior of 2D cutting patterns with triangles

Its possible to constraint Delaunay triangularisation, so that the internal triangle angles are smaller than a given value, or that those triangles have a minimum area value (as seen in Figure 5).

The next task is to identify the 3D avatar to be "dressed" in the virtual environment. Given the synergies that have arisen in a joint European R&D initiative (the Fashion-Me project [1]), we are using the Seamless Generic Avatar from AvatarMe [4] which comprises of 3800 triangles and 1969 vertexes, for a medium resolution version (see Figure 6, left, for a female version). Using this proprietary technology, a generic avatar can be deformed to accommodate the specific characteristics of any person (see Figure 6, right, for a male version), taken from 4 photographs at predetermined positions (a process that takes on average 2-3 minutes). This means that we are able to simulate garment dressing with personalised avatars. After loading the avatar into the 3D scene, we need to position the cutting patterns, now triangularized, in the proximity of the avatar, using 3D Studio MAX specific interactive tools. Correct positioning (see Figure 7) will aid the mechanical simulation phase that follows. Before we initiate the simulation process, we still have to set-up a configuration file (*.cfg*). This one defines general parameters of the simulation, proprieties of the fabrics, loading and boundary conditions. Total simulation time, the time step of each iteration, a precision factor, and the DNS name of the remote E-Fabric server, control the simulation. The linear or non-linear material proprieties of the fabrics (tensile, bending, mass density and thickness) and their visual attributes (texture maps), are defined. Finally, the loading (gravity filed, external wind forces) and boundary conditions of the mechanical system (some particles may be fixed), are also established.

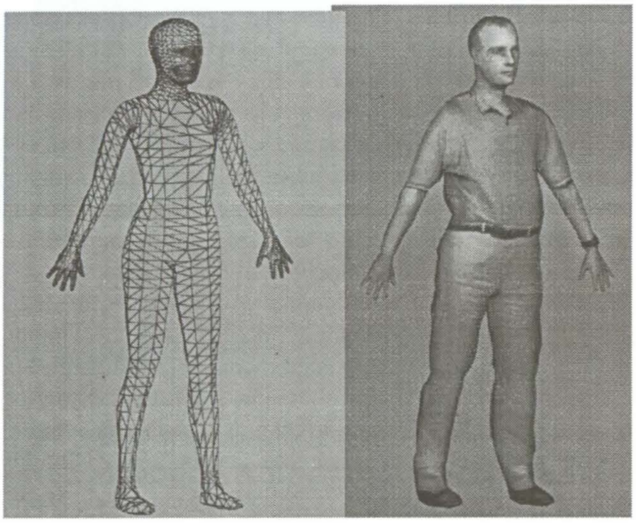

Figure 6 Seamless Generic Avatar, female version (left), and Personalised Avatar, male version, with the real clothes as texture maps (right)

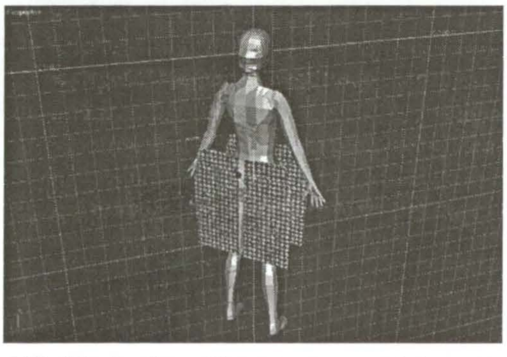

Figure 7 Positioning the cutting patterns around the avatar in 3D Studio (female version)

3. E-FABRIC SERVER

3.1 Computational Model for Plain Woven Fabrics

The server implements a computational model of plain-woven fabrics [5, 6, 21], based in the macroscopic Theory of Elasticity and in principles taken from the Mechanics of Materials. The model is able to represent known elastic behaviour in deformation, such as planar extension and shearing and out-of-plane bending, drape and Euler buckling. The buckling behaviour is present in both shear and compression (see Figure 8, for some examples produced by our model). Cloth is assumed to be an orthotropic linear elastic continuum, discretised by a mesh of triangles. Each triangle, links tree particles and is able to measure the stress and strain of the underlined medium. For planar deformation, we assume the hypothesis of the plate under plane stress, from the classical theory of Elasticity. For the out-of plane deformation, we allow linear elasticity and non-linear displacement in bending, by modelling curvature interactions along the edges of neighbouring triangles. According to the Principle of Superposition, which is valid for linear elasticity, we can sum up the displacements evaluated in each of the two models, to find the total displacement of the surface. The particle system obeys the macroscopic laws of the dynamic equilibrium, according to the Newton's 2nd law formulation. This particle system is subject to several internal and external forces. Non-linear elastic material behaviour is made possible by piecewise linear approximation of measured data (see Figure 11).

The surface of the cloth is modelled with a triangular mesh. Each irregular triangle of the discrete topology, corresponds physically to a set of tree linked strain gauges, referred as a *Strain Rosette* [7], (Figure 9) each one making a different angle with the warp direction. Each strain gauge is able to evaluate (or, in physical terms, measure) the extensional deformation of the underlying continuum, along that specific angle. If we assume a condition of plane stress for each triangle, then it can be shown that the stress tensor takes the following expression [21]:

$$\begin{cases} \sigma_{zz} = \tau_{zx} = \tau_{xz} = \tau_{zy} = \tau_{yz} = 0 \\ \sigma_{xx} = \dfrac{E_x}{1-\nu_{xy}\nu_{yx}}\varepsilon_{xx} + \dfrac{E_x\nu_{yx}}{1-\nu_{xy}\nu_{yx}}\varepsilon_{yy} - E_x\varepsilon_{0xx} \\ \sigma_{yy} = \dfrac{E_y\nu_{xy}}{1-\nu_{xy}\nu_{yx}}\varepsilon_{xx} + \dfrac{E_y}{1-\nu_{xy}\nu_{yx}}\varepsilon_{yy} - E_y\varepsilon_{0yy} \end{cases}$$

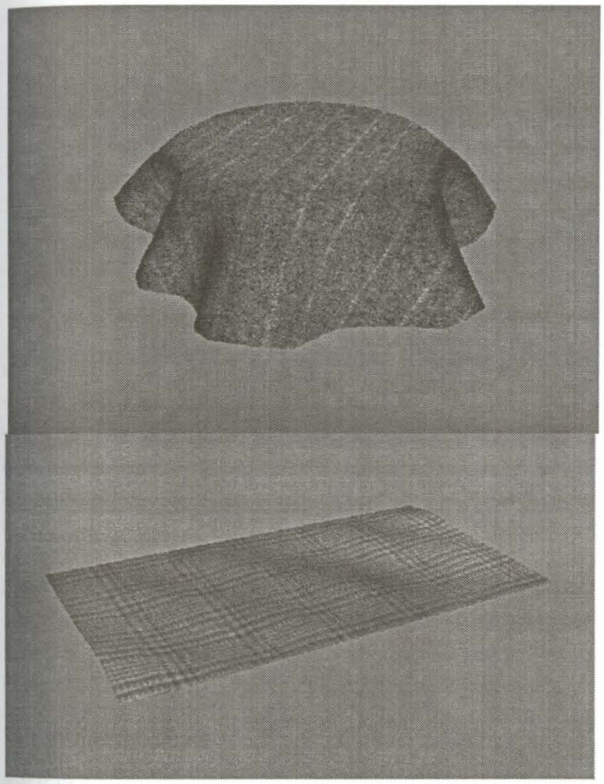

Figure 8 Fabric Draping and Fabric Buckling in Shear

The previous expression is suitable for piecewise linear approximation of non-linear experimental stress-strain relation, which is an innovtive contribution of our model, under the assumption of small planar stresses, from which results small strains, of the hypothesis of the plate under plane stress, for which lienear elasticity is still valid. Cloth, as an orthotropic material, has four independent constants: E_x and E_y, respectively, the Young modulus along the warp and weft directions; G_{xy}, the transversal elasticity modulus; and, ν_{xy} and ν_{yx}, the Poisson coefficients. The symmetry of the elastic tensor imposes that:

$$E_y \nu_{xy} = E_x \nu_{yx}$$

E_x, E_y and G_{xy} can be obtained from experimental data, developing linear interpolations of non-linear data [9, 21] .ν_{yx} can be obtained from the following expression [9]:

$$\frac{1}{G_{xy}} = \frac{4}{E_{45}} - \frac{1}{E_x}\left(1 - 2\nu_{yx}\right) - \frac{1}{E_x}$$

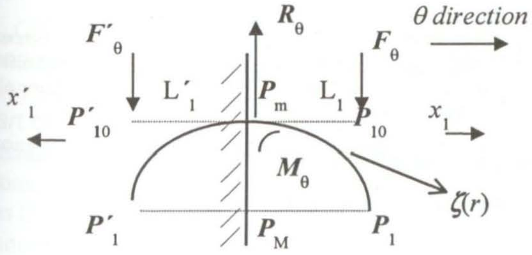

Figure 10: Static equilibrium situation of two cantilever beams fixed in position $\mathbf{P}_m$ and supporting concentrated loads $\mathbf{F}_\theta$ and $\mathbf{F'}_\theta$ in their end points. $\mathbf{P}_1$ and $\mathbf{P'}_1$ are the deflected end positions of the beams.

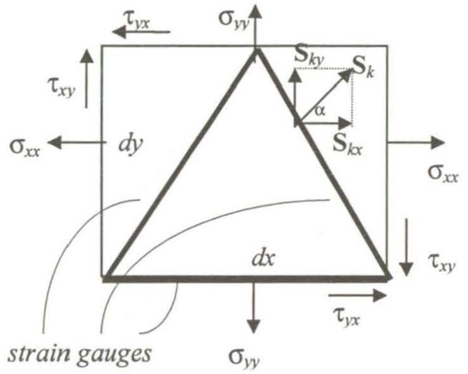

Figure 9: Principal stresses on a dxdy element of a plate under plane stress, with 3 strain gauges attached and organised in a triangle.

We are interested in evaluating the combined stress S_k, applied in an edge k of each triangle (Figure 9). This problem has a simple solution, known for long, from the macroscopic Mechanics of Materials [7]. From the tree local strains (ε_α, ε_β, ε_γ) evaluated by the strain gauges, we derive the principal strains (ε_{xx}, ε_{yy}, $\gamma_{xy} = \gamma_{yx}$), by solving a linear system of three equations. The principal strains are then replaced in stress tensor expressions given, to find the stresses acting along each of the triangles edges. The stresses, in turn, can be converted to forces simply by multiplication with the length of each edge and these are the forces that will drive the dynamic simulation of the planar elasticity.

The out-of-plane deformation model, aims to represent the bending deformation of cloth at large, that is to say, including single and double curvature that occurs in draping conditions, as well as the reversible elastic buckling phenomena that shows evidence in compression and shear. Curvature can be handled, along many possible directions, by considering the angles between triangles that share a common edge. The basic deflection model behaves like a cantilever beam bending across a given edge of the mesh. This hypothesis is illustrated in Figure 11, where we consider, as an example, deflection along a direction that makes a θ angle with the warp. A cantilever beam is fixed in a point $\boldsymbol{P}_m$ belonging to the edge shared between the two triangles (Figure 10) and is supporting a concentrated load $\boldsymbol{F}_\theta$ at the position of particle $\boldsymbol{P}_1$. Another cantilever beam is defined in a similar way for the opposite vertex $\boldsymbol{P'}_1$, supporting a concentrated load $\boldsymbol{F'}_\theta$.

The linear elasticity formulation for the stress-strain relation in this type of deformation, corresponds to the well known Bernoulli-Euler law [7]. Considering bending along cloth´s principal directions, we have: $\boldsymbol{M}_{x,y} = B_{x,y} k \boldsymbol{u}_{x,y}$, where $\boldsymbol{M}_{x,y}$ is the bending moment, $B_{x,,y}$, the flexural rigidity and k the curvature. B_x and B_y can be evaluated theoretically, using the thin plate theory [7, 9] of orthotropic materials or, obtained experimentally for the textile case, using Kawabata or FAST data. If we are looking at the curvature along an arbitrary direction, making an angle θ with the warp direction, the following expression for the flexural rigidity [9] should be used instead:

$$B_\theta = B_x \cos^4\theta + \left(2\nu_{xy} B_x + 4\frac{G_{xy} h^3}{12}\right)\cos^2 \mathrm{sen}^2\theta + B_y \mathrm{sen}^4\theta$$

If we represente the deflection curve of the bent beam, by a parametric spline curve $\zeta(r)$, the curvature at any point along the beam can be calculated, by the following non-linear exact expression, which is again, an innovative finding of our model:

$$k(x) = \frac{\left\| \frac{d\zeta(x)}{dx} \times \frac{d^2\zeta(x)}{dx^2} \right\|}{\left\| \frac{d\zeta(x)}{dx} \right\|^3} = \frac{M_\theta}{B_\theta}$$

The bending moment $\boldsymbol{M}_\theta$ is maximum, where the curvature reaches also a maximum, which happens in point $\boldsymbol{P}_m$. We can easily shown [21], from the static equilibrium conditions in Figure 10, that the bending force at the right extremity is:

$$F_\theta = \frac{M_{\theta\max}(r_0)}{\mathrm{L}_1} = \frac{B_\theta k_{\theta\max}(r_0)}{\mathrm{L}_1}\Bigg|_{\zeta(r_0)=\boldsymbol{P}_m}$$

A similar expression can be found for F'_θ.

To resist such bending deformation, we apply two restoration forces, along the normal directions at each of the extremities of the beams. Each force is equal in modulus to the respective bending force. These pairs create bending moments that elastically resist the curvature deformation of cloth.

Two additional restoration forces are applied at the vertices of the edge along which the bending is taking place (Figure 11). These two later forces are calculated in such a way as to cancel the total force acting on the two triangles, thus maintaining the linear momentum of the system.

This linear elasticity formulation, can also be generalised to a piecewise linear approximation of non-linear elastic stress-strain experimental relations [21].

The equilibrium is evaluated by solving the following ordinary differential equation (ODE), for each surface particle $\mathbf{p}_i$:

$$m_i \frac{d^2\mathbf{y}(i)}{dt^2} + wd\frac{d\mathbf{y}(i)}{dt} + \mathbf{c}(\mathbf{y}(i),t) + \mathbf{g}(\mathbf{y}(i),t) = \mathbf{f}(i,t,\mathbf{y}(i))$$

where m_i is the particle mass, $\mathbf{y}(i)$ is the particle position, w_d is a damping coefficient, $\mathbf{g}(\mathbf{y}(i),t)$ is the resultant of the internal tensile elastic forces of planar extension, compression and shearing (defined earlier for each cloth triangle), $\mathbf{c}(\mathbf{y}(i),t)$ is the resultant of the elastic restoration forces that resists bending and buckling deformation (as mentioned, these forces enable neighbouring triangles to rotate around their common edge) and $\mathbf{f}(i,t,\mathbf{y}(i))$ is the resultant of n external forces, such as gravity field, wind force (applied to all particles), impulsive forces due to the collisions between particles and rigid or non-rigid object triangles and linear elastic forces (these last ones only apply to pairs of particles and are used to enforce seaming constraints).

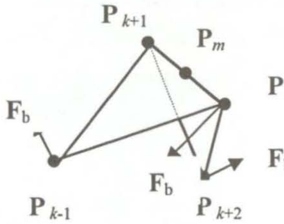

Figure 11: Restoration forces, that resist bending, applied in vertices of two adjacent triangles.

To solve this equation we have used LSODES (*Livermore Solver for Ordinary Differential EquationS*), from the Lawrence Livermore National Laboratory [20], which is tuned to solve stiff ODE equations of the form:

$$\frac{d\mathbf{x}(i)}{dt} = \mathbf{f}(i,t,\mathbf{x}(i))$$

LSODES receives a precision factor, the full current particle system state $\mathbf{x}(i)$ (position, velocity), the starting and end time, a pointer to a function $\mathbf{f}(i,t,\mathbf{x}(i))$ that computes the derivatives of $\mathbf{x}(i)$ (the accelerations) and finally, solves the ODE using an adaptative step explicit method, calling $\mathbf{f}(i,t,\mathbf{x}(i))$, as many times as needed to reach the end time with the required precision. The algorithm of the server goes like this, for each time step iteration:

```
1. Handle collision detection and response
   between particles and rigid body triangles,
   enforcing restrictions to particle forces
   and velocities if there are collisions
2. Handle self-collision detection and
   response between particles and deformable
   body triangles, enforcing restrictions to
   particle forces and velocities if there are
   collisions
3. LSODES solver computations, ignoring
   collisions
4. Handle seaming computations.
```

In the architecture, the client-server communication uses the following protocol:

```
Establish client-server connection
```

```
While simulation is proceeding do
    server solves equilibrium equations
    through time, using LSODES and computes
    particle system state of frame_i
    server sends frame_i
    client receives frame_i
    client visualizes frame_i
end while
Close client-server connection
```

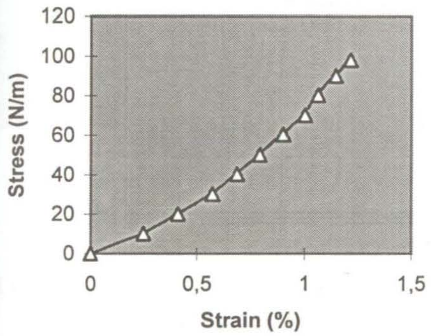

Figure 12 Sucessfull comparison between the experimental stress-strain curve obtained in a Tensile Tester on the cloth's warp direction, (triangles) with the one simulated by our method (line), using a piecewise linear approximation

3.2 Handling Collision Detection amd Response

The server handles the collision detection of moving particles against rigid and deformable body triangles in a optimised way, since it organises spatially both the particle system and the rigid bodies, that are present in the scene, using an octree scheme. Our algorithm only considers the test of a moving particle against rigid and deformable body triangles, that are within the proximity of the particle [21], since we intersect both octrees, prior to the collision detection tests. If a collision is detected, the algorithm returns the colliding point in the triangle surface and the normal **N** at that point, which will be used in the collision response stage.

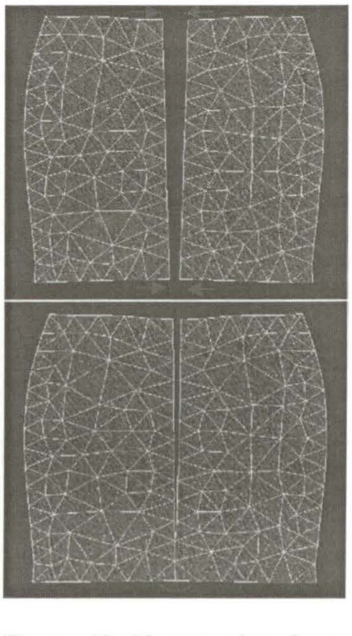

Figure 13 Linear spring forces between particles pairs (of seams), eventually joining cutting patterns

3.2.1 Collision response when the colliding particle is not part of a seam

We handle inelastic collisions, that is, as soon as the a particle strikes the avatar surface (with normal N) using force **F**(*i*), we cancel the normal component **Fn**(*i*) of this force, maintaining the tangential one, **Ft**(*i*) (which equals the resulting force **Ff**(*i*)). We proceed with the same technique for the velocity of the striking particle. Thus, after the collision, the particle will slide along the avatar surface, with the following tangential force and velocity, where **N** is the unit normal of the triangle plane:

$$\mathbf{F}_f(i) = \mathbf{F}(i) - (\mathbf{F}(i).\mathbf{N})\mathbf{N}$$
$$\mathbf{V}_f(i) = \mathbf{V}(i) - (\mathbf{V}(i).\mathbf{N})\mathbf{N}$$

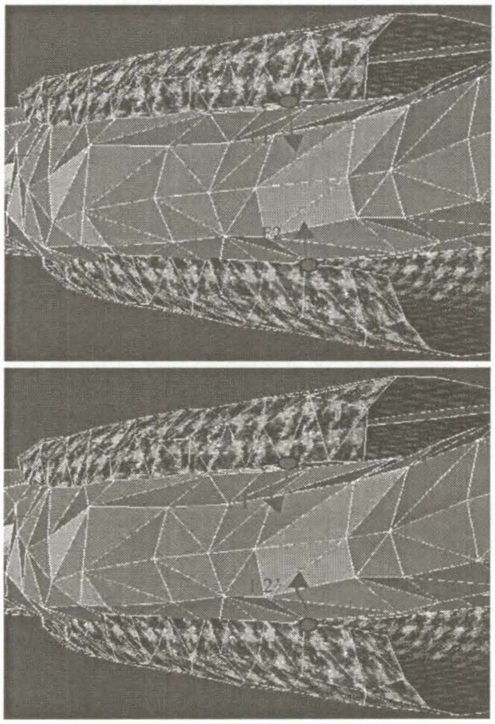

Figure 14 Handling collision response when the colliding particle is part of a seam

3.2.2 Collision Response when the colliding particle is part of a seam

If a colliding particle is part of a seam pair, and the seaming process is ongoing, we need to adjust the inelastic response to this collision case, so that the cloth particle slides along the avatar surface, but still maintains its attraction towards the opposing particle in the seam, which will lead to their mutual fusion. In the first image of Figure 14, we see cloth particle 1 colliding with the avatar with force **F1**, and its seam pair, cloth particle 2, colliding with the avatar with force F2. The response is depicted in de second image of the same figure, where, for particle 1, we compute a new resultant force **F1′**, whose direction is tangential to the avatar surface and corresponds to the projection of **F1** in that surface, and whose modulus is |**F1**|. For particle 2, we apply the same method. This will ensure that the cloth particles have a slide contact with the avatar surface, but are still attracted one to the other. The general expression for the force and velocity after the collision is :

$$\mathbf{F}_f(i) = |\mathbf{F}(i)|\,(\mathbf{Unit}\ [\mathbf{F}(i)] - \mathbf{N})$$
$$\mathbf{V}_f(i) = |\mathbf{V}(i)|\,(\mathbf{Unit}\ [\mathbf{V}(i)] - \mathbf{N})$$

3.3 Handling Seams

We handle the process of joining cutting patterns, by introducing springs between each particle pair of a seam (see Figure 13), which attracts each of them to the other. During the simulation, and whenever the distance between particles fall below a given threshold, we assume that a seam point is created and we eliminate, from the cloth topology, one of the particles, thus maintaining the other (the surviving particle). This process involves re-structuring the particle system data structure at the server side, namely the corresponding geometry data structure (the list of triangle vertexes, where one vertex is eliminated), the edge data structure, since for some edges, a vertex is eliminated and other is added, and the triangle data structure, since for some triangles, one vertex is eliminated and other is added as well. Duplicated edges may also appear, and these must be eliminated. We should note that at the client side, we do not re-structure the cloth's geometry and topology. In fact, when a cloth particle is eliminated, it still lives in the client, with the same attributes of its surviving particle pair of the seam.

3.3.1 Compressing and Decompressing E-Garment Simulation Results

Simulation results, which keep the complete E-Garment animation simulation through time (that is, a set of connected particles, which follows a trajectory over time), are stored in a file using our own binary format, referred to as **.trj** (from **tra**jectory). Large file sizes are easily acheived, of the order of several Mbyte. To exchange such type of files over the Internet, for example, raises a number of problems, due to the best-efforth, variable bit-rate (seldom low bit-rate) caractheristics of such a communication medium. To tackle this we have proposed in a previous paper "Wavelet Compression and Transmission of Deformable Surfaces over Networks" [23], a compression and decompression technique, that allows the minimization of the size of the E-Garment animation data, hence decreasing the total transmission time, based on the time-localized feature of the wavelet transform. Our system supoprts this technique and, as result, the user can also save the E garment simulation results (usually keeped in the binary **.trj** file format) in our own compressed file format called **.wvt** (from **w**a**v**ele**t**).

The process of compressing may take some time, depending on the size of the trajectory file and it yields better results with large trajectory files, although satisfactory results are also obtained with smaller **.trj** files.

4. RESULTS AND DISCUSSION

In figure 15 we depict a structural mechanics test proposed by Prof. Eichen in [24] as a standard way to compare and evaluate different cloth models solving a complex problem with a well-known analytical solution. The problem is just of a cantilever beam that bends under a concentrated force at the free end. No gravity or other forms of distributed loads are present. This problem involves linear elasticity and non-linear displacement in bending and has a well-known analytical solution, which can be found by solving elliptic integrals [7]. The cloth models tested and compared are ours ("***Stran-Rosette-Canteliver Beam*** – **SR-CB** model), a precise particle based cloth model proposed by Prof. Eichen in [24] and the analytical solution. Figure 15 depicts the results obtained while evaluating the *dx* displacement of the test,

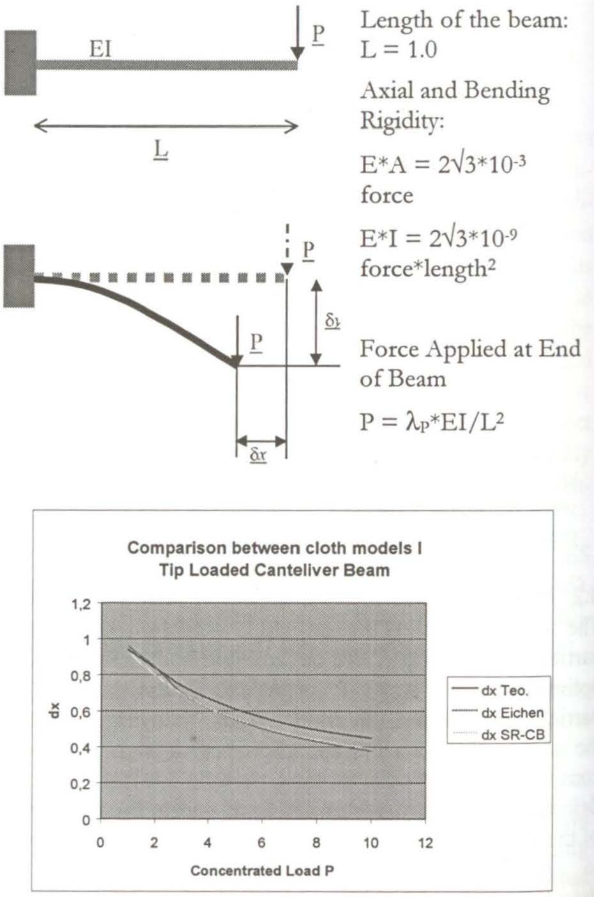

Figure 15 Standard Tip Loaded Cantilever Beam Test set-up conditions and comparison results

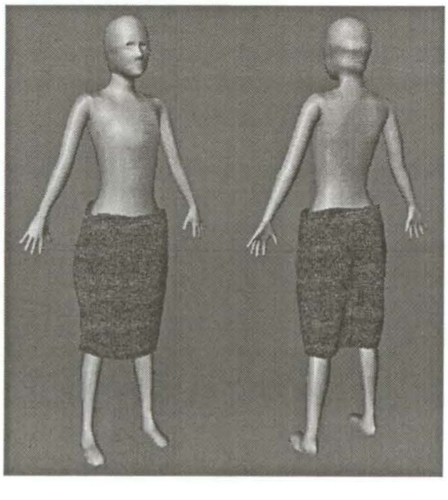

Figure 16 Dressing a personalised female avatar with a skirt, by seaming CAD cutting patterns around the avatar body

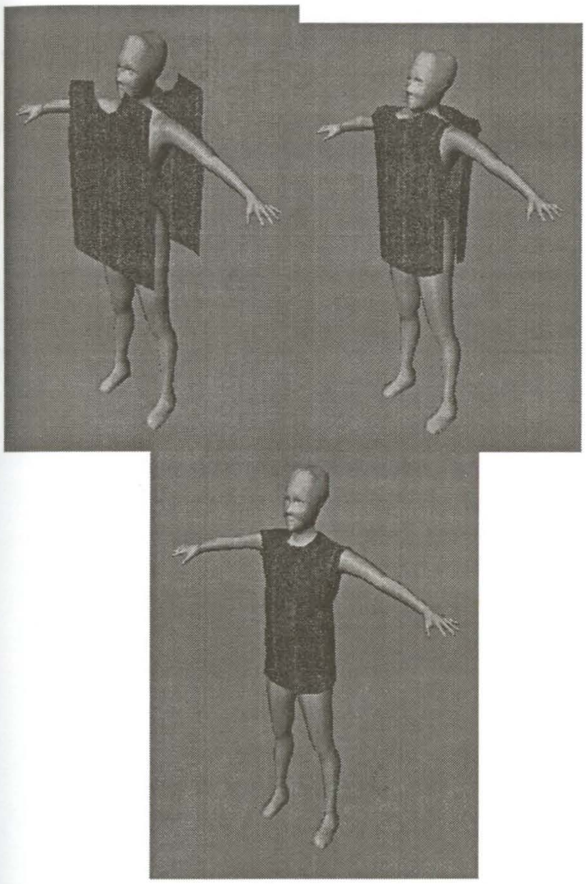

Figure 17 Dressing a personalised female avatar with a simple garment

using the analytical method, Eichen's reported figures and our calculated figures. Our model and Eichen´s agree and both follow closely the theoretical results.

In Figure 16 we can visualise two frames, rendered with Texture Mapping and Gouraud shading, of a simulation were we have dressed a personalised female avatar with a skirt. The frames correspond to the final state of the simulation. As mentioned earlier, the avatar comprises 3800 triangles and the tree skirt cutting patterns, have 403 vertexes and 674 triangles after the seaming simulation. The simulation took approximately 300 seconds of CPU, for the seam-joining process and 900 seconds, for the full simulation (seam-joining and dressing around the avatar's body), in a O2 SGI machine, featuring a MIPS R10000 CPU (195 Mhz) and 256 Mbyte of RAM. The results were as follows:

- Simulation results **.trj** file (uncompressed): 1.845 Mbyte, 18 sec of simulated time.
- 61% compressed **.wvt** file: 703 Kbyte.

In Figure 17 we depict three frames of a simulation of a dress draping over a female avatar. The dress model comprises 398 vertexes and 686 triangles after the seaming simulation. The acheived simulation results, were:

- Simulation results **.trj** file (uncompressed): 1.275 Mbyte for 13 sec of simulated time
- 57% compressed **.wvt** file: 547 Kbyte

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

We have demonstrated the validity of our new computational framework for modelling the behaviour of plain-woven fabrics and for simulating electronic garments made of this material. This comes from the fact that our model is mechanically precise and follows well experimental data. The method requires the availability of "fabric fingerprints", that is, fabric material data extracted from real-life quality control experiments of cloth. We have performed simulations with simple garments dressed on avatars, which were obtained from real people. We have achieved interesting results, from the visual and mechanical point of views. Therefore, we are confident that our method and system architecture is valid for the production of plain-woven virtual textiles and virtual garments for electronic commerce applications. Currently we are enhancing our model in the process of "dressing" animated avatars representing humans, with electronic garments. For this, we are improving our algorithm for collision detection between the textiles and the moving avatars, considering also auto-collision between the fabrics themselves. The numerical algorithms are being optimised for speed and accuracy and an implementation of the E-Fabric server on Vitara [22], a Linux-based parallel "beowulf" cluster, over PVM (Parallel Virtual Machine), is currently under way [25], showing already promising reductions of the total elapsed simulated time. The end-system will be the basis for an Internet-based electronic commerce solution for on-line shopping of apparel and fashion goods.

6. ACKNOWLEDGEMENTS

The authors want to thank Vasco Nina from Maconde, Portugal, Steven Crampton from AvatarMe, UK, Andrea Mueller from IAT, Germany, Thanassis Kountzeris from Mellon, Greece, Rui Silvestre, António Lopes, Luis Monteiro Dias, Rafael Bastos and Pedro Santos, from ADETTI and the remaining partners of the Fashion-Me project, for their valuable contributions to this work.

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Notation

x, y	directions of the warp and weft
$\mathbf{r}$	displacement vector
$\mathbf{v}$	velocity vector
$\mathbf{a}$	acceleration vector
σ_{ij}	stress tensor (elastic tensor)
ε_{ij}	strain tensor
$\sigma_{xx}, \varepsilon_{xx}$	extensional stress/strain warp
$\sigma_{yy}, \varepsilon_{yy}$	extensional stress/strain weft
τ_{xy}, γ_{xy}	shear stress/shear angle
$\mathbf{S}_k$	stress in edge *k* of a triangle
$\mathbf{u}_x, \mathbf{u}_y$	unit vectors
$dxdy$	elementary surface element
α, β, θ	angles
E_x, E_y	Young modulus
ν_{xy}, ν_{yx}	Poisson ratios
ε_{oxx}	residual strain
G_{xy}	transversal elasticity modulus
E_{45}	Young modulus, bias direction
$\mathbf{M}, \mathbf{M}_\theta$	bending moment
k, k_θ	curvature
$\zeta(r)$	spline curve
B_x, B_y, B_θ	flexural rigidity
w_i	damping coefficient
m_i	particle mass
$\mathbf{f}^n$	resultant of force vectors
L_1	equilibrium length of the beam
x_1	coordinate along the bent beam
$\mathbf{g}_k$	tensile force
$\mathbf{F}_b$	restoration force resisting bending
$\mathbf{F}_1, \mathbf{F}_\theta$	concentrated load
$\mathbf{R}_\theta$	reaction force
$\mathbf{d}k$	separation of vertices