ACM Symposium on Solid Modeling and Applications (2004)
G. Elber, N. Patrikalakis, P. Brunet (Editors)

Physics-based Modelling and Simulation of Functional Cloth for Virtual Prototyping Applications

M. Fontana, C. Rizzi and U. Cugini

Dipartimento di Meccanica, Politecnico di Milano, Italy

Abstract

A CAD-oriented system is proposed for the design of complex-shaped functional cloth, provided with a physics-based modelling core for simulation and virtual prototyping tasks. Textiles are physically modelled as particle grids in 3D space subjected to Newtonian dynamics, with internal spring, bending and shear forces derived from KES-F data measuring material behaviour. Interactions with the environment are expressed as external forces, collisions against obstacles, self-collisions and constraints. Differently from physics-based animation systems, the proposed system is conceived for real design purposes, and includes functionalities emulating the construction process of actual clothing and structural textiles, e.g., mesh sewing/assembly, insertion of small components, multi-layered fabric composition, mechanical shape deformation, and 2D-to-3D mapping methods. As applications, several cases of textile configurations are considered, with geometric models directly provided by industrial companies and presenting different levels of design complexities, such as garment models (e.g., men's jackets) for the clothing sector, or functional textiles used in the automotive industry (e.g., soft car tops).

Categories and Subject Descriptors (according to ACM CCS): I.6.3 [Simulation and Modelling]: Applications; J.6 [Computer-Aided Engineering]: Computer-aided Design

---

1. Introduction

A great interest has been recently addressed to cloth modelling for computer animation tasks and the computer-aided design of apparel and functional cloth.

In this work we are mainly concerned with cloth modelling and simulation for industrial design purposes. Apparel and upholstery manufacturers use, in fact, a well-established 2D CAD technology for pattern drafting and sizing, or CAM systems for automatic cutting and sewing; yet, they claim the lack of more enhanced 3D CAD systems provided with simulation capabilities, to predict the actual behaviour of cloth before, and instead of, any physical prototyping. Our motivation is thus the integration of physics-based modelling within computer-assisted cloth design as a strategic issue for a new conception of CAD systems endowed with virtual prototyping tools.

Several *geometric* and *physics-based* methods have been proposed for modelling cloth. Purely geometric models can be adequate for broadly realistic animations; nevertheless, a physics-based cloth representation becomes necessary for accurate prediction and simulation purposes, taking into account mechanical properties of materials and interactions with the external environment.

A detailed overview on earlier theoretical cloth models proposed by the textile engineering community is presented in Breen's survey in [HB00]. As regards physics-based cloth modelling in computer graphics, several *continuous* and *discrete* approaches have been proposed since the mid 80's.

Continuous models, generally leading to PDE problems, interpret textiles as continuous media, e.g. subjected to elasticity laws, wave propagation and fluid dynamic laws (as in [TPB*87,EDC96,Ao90, LDG96]). However, the inherently "discrete" structure of cloth threads and its highly flexible behaviour seem to be better described in terms of discrete representations such as *particle-based* models, with textiles modelled by structured or unstructured particle grids, subjected to internal/external forces and embedded in Newtonian [Pro97,VM00] or Lagrangian [EW96] dynamics, or in equilibrium configurations determined by energy minimization criteria [Fey86,BHW94]. Recently, a great interest has been addressed to efficient implicit and semi-implicit time discretization techniques for ODE systems generated by cloth's particle-based grids [BW98,HEE*02,BMF03].

For a detailed overview on physics-based modelling, see [NG96, HB00,VM00]. What emerges from the above models is the rapid progression towards increasingly realistic cloth animations at increasingly low computational times [CK02,VM00,BFA02]. Nevertheless, simple-shaped one-layered cloth pieces were generally considered, or overall cloth surfaces emulating apparel in its global and visually pleasant effect, but not modelling functional and construction details. What is generally missing is the application of these methods to complex-shaped cases of real interest, i.e. actual cloth as it is conceived by manufacturers for production tasks. Our contribution is, instead, the definition of CAD-oriented system with physics-based simulation for virtual prototyping tasks, as shown in the next Sections, incorporating construction aspects from single fabric pieces up to complex-shaped assembled textiles, exchanging data and validating results with industrial manufacturers.

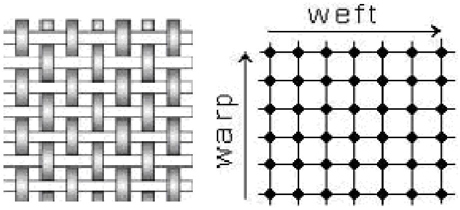


Figure 1: *A typical particle-based model for a woven pattern.*

2. Particle-based Model for Cloth Layers

Cloth is a deformable material, quite resistant to in-plane tension and extremely flexible under out-of-plane bending stress. We here consider *woven* textiles, as they have the widest application in cloth manufacturing, characterized by a structured thread pattern with threads interlaced along two (generally orthogonal) directions, the *warp* and the *weft* (Figure 1).

To predict the physical behaviour of real cloth, we need to consider mechanical properties depending on the textile material. To this aim, we use data about textiles provided by the Kawabata Evaluation System of Fabrics (KES-F), a system for fabric's hand evaluation, which measures thickness and mass density, deformation under tension, compression, bending and shear stress, friction and other properties depending on the material [Kaw80].

A simple, though efficient, model for representing the discrete structure of interlaced threads in a woven cloth layer is the discrete particle-based approach (Section 1). Thus, similarly to Breen et al.'s [BHW94] and Provot's models [Pro97], we start by associating to each fabric layer a structured 2D grid with coordinate lines defined from warp/weft directions. Particles are associated to grid nodes, located at regularly distributed interior warp/weft thread intersections, or intersections with the border. Figure 2 shows the chosen layer's discrete particle grid, with triangular elements obtained by adding diagonals, and distribution of internal forces defined from grid's topology. Internal forces are described as linear *spring* forces, to model behaviour under tension and compression, or linear torques, to model reaction to *bending* and *shear* (also named *trellising*).

Extracting from KES-F data the elongation ratios ε_x and ε_y under tension along weft and warp, the bending rigidity B and the shear stiffness G for a certain fabric, easy computations provide

$$k_{Sx} = \frac{F_S h_y}{\varepsilon_x h_x}, \quad k_{Sy} = \frac{F_S h_x}{\varepsilon_y h_y}, \quad k_T = G h_x h_y \cos\Phi, \quad k_B = \frac{B\pi}{180} \qquad (1)$$

as estimates of constants for spring forces [N/m] along weft and warp, and torsional moments for trellising and bending [$N\,m/degree$], respectively [Gal01]. In Eq. (1), F_S is the magnitude of the known imposed force per unit length causing fabric's tension or compression, Φ is the (known) shear angle, while h_x and h_y are grid cell sizes along weft and warp.

As our aim is to predict cloth shapes under equilibrium or environmental low forces (e.g. gravity, wind), we assume non-linear strain and hysteretic cloth behaviour to be negligible. Further details about the particle-based model for cloth layers can be read in [Gal01].

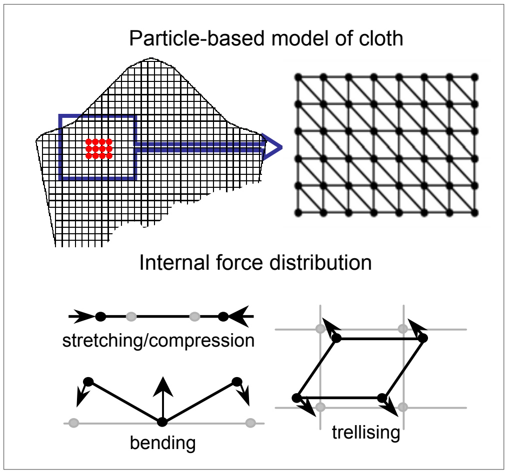


Figure 2: *Particle grid and internal force characterization.*

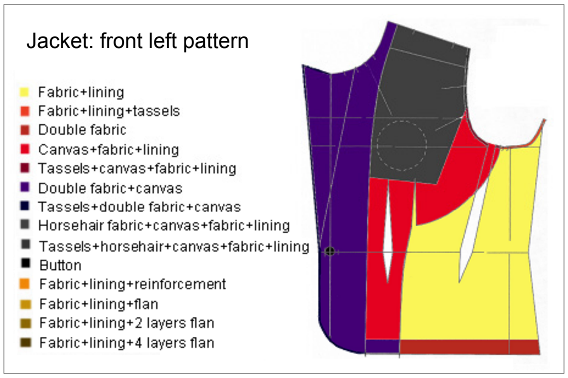


Figure 3: *Multi-layered front panel of a man's jacket.*

3. Extended Model for Multi-layered Assembled Cloth

A particle-based model for single fabric layers (Section 2) is not sufficient to model all characteristics of actual cloth, as it is produced by industrial manufacturers. Figure 3 shows, for instance, the complex multi-layered composition of the front panel of a man's jacket, characterized by different textiles, reinforcements, tassels, stitches and seams. Layers, reinforcements and seams also abound in functional textiles such as tarpaulins and coverings.

From a procedural point of view, though built from different materials and 2D shapes and evaluated according to different functional and aesthetic criteria, garments and industrial textiles are obtained from conceptually similar design stages. Both categories need: definition of 2D fabric patterns, fabric assembly (e.g., by sewing or layer overlapping), border and interior finishings, insertion of small functional/aesthetic components (e.g., buttons, hooks, stuffings, etc.), mechanical/chemical treatment for shape deformation (e.g., pleats, ironing, starching), and 3D configuration/placement over supports or external objects (mannequins or other rigid structures).

Thus, to extend the original particle-based model for one-layered fabric to real clothing and textiles, we consider proper algorithms that locally modify/upgrade the geometry and topology of the initial cloth's particle grids and corresponding discrete physical data (e.g., particle masses, force parameters). The purpose is to emulate some of the above design steps - i.e., sewing of fabric panels, insertion of darts, layer overlapping, insertion of buttons/hooks and final placement of the full cloth model in a space configuration - before enabling 3D physical simulation.

3.1. Sewing Processes

For sake of simplicity, we interpret *sewings* as unary or binary relationships, i.e. involving one or two fabric components at a time, and locally preserving the "manifold" behaviour. These constitute the basic single seams considered in cloth manufacturing. In our future analysis, however, we will consider also multiple sewings, involving more than two components.

The counterpart of a sewing process from the point of view of the particle-based model is essentially a mesh assembly operation accompanied with local modification of the internal force distribution. We implemented a new algorithm in which panels' particle grids to be pairwise connected can present a different number of particles at the border segments (we say that the two grids can be locally *non-conformal*), as it occurs in case of a different particle resolution between the two panels, or in case of complex-shaped borders. Among other mesh assembly algorithms between non-conformal grids, see Turk et al. [TL94].

Figure 4 shows a sewing process between two particle grids of fabric panels. Suppose a panel *A* has to be sewn with a panel *B*: geometrically, this corresponds to know a one-to-one mapping between a given sequence of consecutive oriented border segments of panel *A* with another given sequence of oriented border segments of panel *B*. The sewing algorithm is then a grid assembly procedure progressively merging each sewing segment pair of the mapping.

For each segment pair, let *n* be the number of original particles of the segment in *A* (named *A-segment*) and *m* the number of original particles of the corresponding segment in *B* (*B-segment*).

If the number of particles is different, say $n<m$, then $m\text{-}n$ particles will be added to the *A*-segment in proper intermediate positions to define a "local" one-to-one mapping also between particle pairs, as follows. First, one by one, we progressively search for *n* ordered original particles of the *B*-segment having relative line abscissa values in the segment that are as close as possible to the relative line abscissa values of the *n* particles of the *A*-segment. Practically, this corresponds to finding out the particles in the more-refined segment that have a relative distribution in the segment as similar as possible to the particle distribution in the less-refined segment: this is the local particle-to-particle mapping within the segment pair. Then, the particle grid in the *A*-segment is refined (in one or more parts, depending on the local mapping) along each original grid edge having as a vertex a particle excluded from the local mapping, for a total of $m\text{-}n$ new border grid edges, with corresponding local re-triangulation around the sewing segment pair at the side of the *A*-segment.

Thus, when definitively *A*-segment and *B*-segment have the same number of particles, say again $n=m$ for simplicity, each *i*-th particle of *A* is merged with the corresponding *i*-th particle of *B*, for $i=1,2,...,n,$ by moving particle pairs to an intermediate position. *n* particles belonging to one of the two border segments are then removed from one side. Correspondingly, the mesh topology (grid particles, edges, triangles) around that side is updated similarly to any standard mesh assembly algorithm, now involving conformal meshes. Internal force values are re-computed around the sewn edges with particle mass summation and value increment of the constants of bending forces for all sewn edges.

Although the single panels have originally structured meshes (Section 2), the sewing process generates a final assembled mesh that is locally unstructured around the poly-line of the seam, i.e. along edges and triangles having some vertex on seam's segments. We then estimate spring constants associated to those edges by Van Gelder's method [Van98] based on elasticity theory. An alternative approach to estimate spring constants on edges with arbitrary direction is under development, based on Dias et al.'s work [DGR00], considering stress-strain relations for a linearized elastic orthotropic material.

Note that dart insertion is again a sewing operation, as darts can be regarded as special seams along a fixed sequence of edges, in which panel *B* coincides with panel *A*. In other words, one or more vertices are sewn with one or more vertices belonging to boundary loops of the same panel.

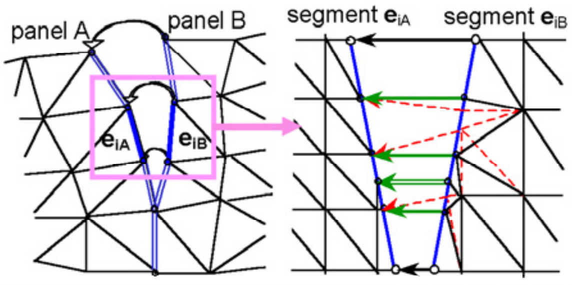


Figure 4: *Sewing between two panels:* (1) *Seam along a sequence of adjacent border segments.* (2) *Details of sewing on a segment pair. Dashed lines show the original particle grid before sewing.*

3.2. Modelling Other Textile Effects

Other textile manufacturing effects can be modelled through ad hoc geometric algorithms modifying particle meshes and local force distributions.

Multi-layered fabrics, for instance, are widely employed to create reinforcements for textiles used in daily clothing (e.g., stuffings and linings in jackets and coats, as shown in Figure 3), protective wear for sport and working activities, as well as coverings, tarpaulins and other textiles used in home/vehicle furnishings, architectural structures, etc. For this reason, the effect of *layer overlapping* has been modelled to consider the presence of several fabrics that may have to be placed/stuck on top of each other. Each layer is identified with a sub-region of the main panel's geometry, composed of a further (equal or different) textile material. The idea is to change physics-based properties (masses, and spring, bending and trellising forces) associated to grid entities (particles, edges, triangles) located inside layer's region, substituting them with proper values that include all effects of single layers by the effect of a unique equivalent material.

When neglecting sliding effects, e.g. for fabric layers that are stuck with each other, the simplest way is to derive grid parameters from additive formulas of parallel spring and torque networks. Presently, we are modifying internal force parameters (e.g. by adding damping terms) to include frictional effects when some sliding occurs between pairs of overlapped layers constrained at the borders. When layers present partially unconstrained borders, however, we compute friction and contacts directly within the model dynamics, e.g. similarly to [BFA02], by maintaining information of each different layer grid.

We considered also possible *insertion of small components* such as buttons and hooks. The effect of buttons intervenes when two panels to be connected are sufficiently close to each other. A possible solution can be simulating the effect of buttons and hooks as kinematic constraints, between pairs of particles located at buttons and hooks' positions, handled during the management of bilateral constraints in the successive dynamic simulation phase (Section 4). A more trivial solution, though effective, is a pointwise correction of particle-based model's topology. Each virtual button/hook can be modelled by connecting the two grid points closest to the required position, imposing a significantly hard spring force and mass increment.

Once the particle grid has been assembled and modified in its geometric/physical parameters, the corresponding 3D configuration is then defined. The textile shape is placed against 3D rigid objects located in the scene to be simulated, according to *mapping laws from 2D onto 3D*. The mapping problem had been already raised by Okabe et al. [OIT*92], proposing the first CAD-oriented prototype for apparel physical simulation.

Similarly to Okabe et al., to drive the 2D→3D mapping procedure we associate triangulations to the planar panels to be mapped onto the surfaces of rigid supports; differently from the former, however, we perform a spreading out that maintain the isometry of each panel's edge and triangle, to avoid local in-plane stretch/shear deformation. For similar reasons, we could not consider the 2D→3D fitting approach by Aono et al. [ABW01], based on inextensible Tchebychev nets, since it cannot prevent from shear deformations. As mannequins and supports have non-developable external surfaces, in general, the 3D placement of cloth panels is applied by considering certain small offset distances, used to define simply-connected *offset* supports/mannequins having locally developable sub-regions (e.g., conic). Panels' sub-regions are mapped onto corresponding sub-regions of the offset supports, up to minimum tolerances, considering initial directions to drive the mapping. Details about mapping algorithms are presented in another work under preparation.

Further details about cloth modelling and construction phases, applied to industrial test cases, can be read in Section 5.

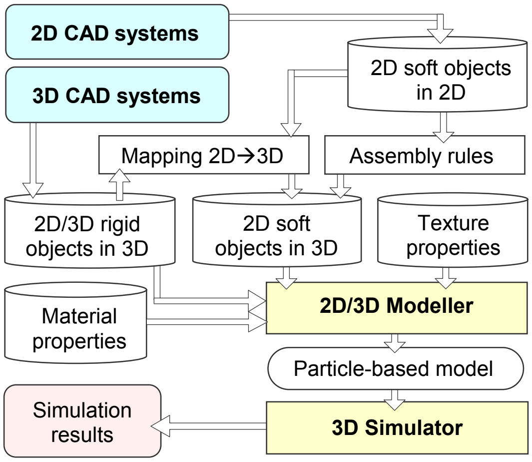


Figure 5: *System's high-level architecture.*

4. Dynamic Simulation

Cloth's final particle-based model is a system $S = \{P_i : i = 1,..,N\}$ of N particles, with masses m_i, positions $\mathbf{r}_i$ and velocities $\mathbf{v}_i = \dot{\mathbf{r}}_i$, for $i = 1,2..,N$. Known the initial configuration from the mapping algorithm, system's dynamics is then governed by the well-known initial value ODE problem derived from Newton's laws $m_i \ddot{\mathbf{r}}_i = \mathbf{F}_i$, $i = 1,2..,N$, with $\mathbf{F}_i = \mathbf{F}_i(\mathbf{r}, \dot{\mathbf{r}}, t)$ sum of all *active* and *reactive* forces acting on particles *i*, and solution $\mathbf{r} = (\mathbf{r}_1,..,\mathbf{r}_N)$, system configuration at each time *t*. Active forces result from the sum of external and internal (spring, bending and trellising) forces. Reactive forces result from *constraints* (e.g. fixed positions, fixed distances or trajectories), from solution of a linear system obtained by the *dynamic constraint* method, a generalized Lagrange multipliers' technique [BB88].

According to Provot [Pro97], we used a modified two-step Euler scheme for the time discretization of the Newtonian ODE system, with collision analysis between the two computation steps. To make computations faster, implicit time discretization schemes are under implementation, according to ideas suggested by [HEE*02].

At each time step of the simulation, *collisions* against rigid supports and *self-collisions* between cloth patches are detected. Among several collision detection techniques (e.g. voxel and octree subdivision, bounding box structures, proximity tracking and curvature–based methods [Pro97,VM00,BFA02]), we adopted *axis-aligned bounding box* (*AABB*) hierarchies with region subdivision, as a good compromise between simplicity and efficiency. In the collision response phase, the velocities of colliding particles are computed by handling collisions as unsatisfied unilateral constraints $d_i(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_N, t) < 0$, $i = 1,2,...,s$, where s is the number of collisions at a certain time, from solution of a linear system again generated by the dynamic constraint approach. Constrained Newtonian dynamics is a well-known context, so we skip details. However, further information can be read in [Gal01].

Details about the implemented system and the graphical interface are here omitted, as presented in [FRC03]. To sum up, Figure 5 shows system's high-level architecture, with data flow up to/from modelling stages (Section 2-3) up to simulation phase (Section 4).

5. Applications

To validate the system within a CAD framework for real cloth design, we collaborated with industrial manufacturers in the textile sector, providing us data about 2D panel geometries, textile materials and construction details (e.g., seams, stitches, layers). The next Sections present the adopted methodology and show simulation results for 1) apparel production (e.g., men's jackets), 2) functional modelling and simulation of textiles for the automotive industry (e.g., car sunroofs).

5.1. Design of Apparel

Activities on garment design were first carried out within the Brite-Euram Project *MASCOT* (*Intelligent 3D Design and Simulation System for the Clothing Industry*), in collaboration with CAD/CAM developers and clothing companies, aiming at developing an integrated 2D/3D design and simulation system for women's apparel production. Modelling phases and simulation results were presented in [BGR00].

Further activity was done within the national project *Consorzio TA2000* (*Textile/Apparel Consortium 2000*), in collaboration with several Italian clothing companies, with the purpose of developing systems and methods for virtual men's apparel prototyping.

As known, men's fashion is characterized by rather standardized garment shapes, differently from women's. Differences between one season and the other are in small shape details and material/color combination. For this reason, 3D geometric models were first derived by reverse engineering techniques, from digitalization of existing apparel articles. Men's jackets were considered, as significantly complex test cases (Figure 3), with models provided by F.lli Corneliani SpA (*www.corneliani.com*), an italian manufacturer of men's clothing. Figure 6 summarizes the main geometric and physical modelling steps that were carried out.

A modification interface was implemented, based on Maya Deformer tools by Alias|WaveFront (*www.alias.com/eng/products-services/maya*), to allow interactive modification of sizes and proportions of jackets' functional parts (sleeves, shoulders, breast, waist, etc.), acting through free form deformation driven by characteristic lines defined on the geometric model (Figure 6-1).

Export modules could automatically generate files containing information in a proper format, as input for 2D panel extraction, obtained through a F.lli Corneliani's owner CAD software (Figure 6-2). Panels' particle-based grids were obtained through our particle-based modelling approach (Figure 6-3), using information about materials, layers, buttons, seams and darts again provided by F.lli Corneliani. Panel grids were then assembled together on virtual mannequins by using 2D→3D mapping rules depending on mannequin's shape (Figure 6-4). Once the particle-based model was created in 3D, physics-based simulation could be then performed for specified time intervals.

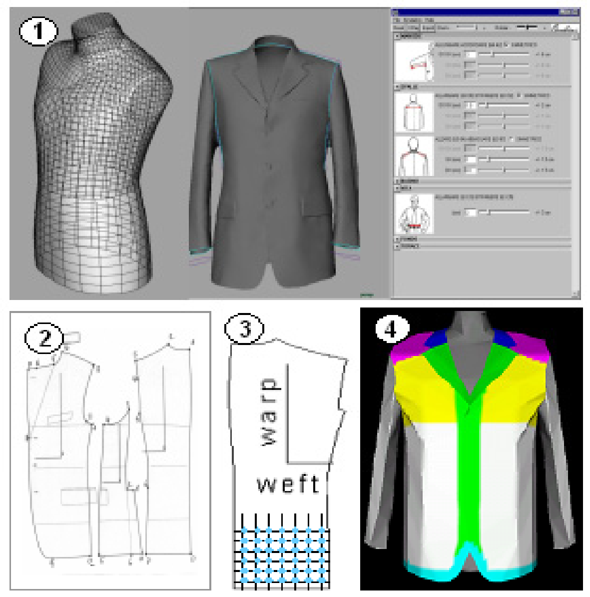


Figure 6: *Virtual apparel design:* (1) *3D geometric model and modifications.* (2) *Extraction of 2D panels.* (3) *Panels' particle-based model.* (4) *Pre-simulated 3D particle-based model.*

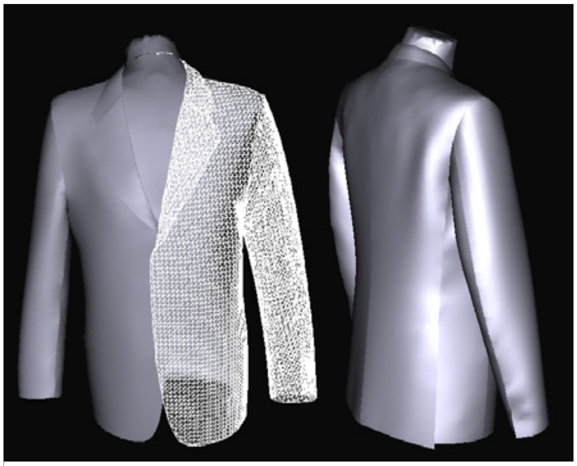


Figure 7: *Some views of a simulated jacket.*

Number of particles	13935
Number of triangles	27464
Number of rigid body points	1484
Number of rigid body triangles	2608
Time Step (ODE solver)	2.0 e-5
Computation Time	1 h 43' to simulate 0.1 sec

Table 1: *Computational times for jacket's simulation.*

Figure 7 displays overall front and back views of the simulated jacket. The wireframe mode of the left front side of the jacket shows the underlying particle grid used for physics-based simulation.

Validation of results was done in collaboration with F.lli Corneliani company and other project's partners. Results, as shown in Figure 7, were considered significantly accurate, as a confirmation of the validity of our physics-based approach. We aim, however, to get more precise results in some critical structural jackets' parts, e.g. around the collar and shoulder borders, by executing further KES-F measurements on stuffings and linings used as reinforcements.

Differently from female models previously studied [BGR00], finer particle meshes and higher computational times were required for the simulation tests on men's jackets. This was expected, as jacket models have more complex shape with a large number of panels, multi-layered fabrics (e.g., linings and stuffings), and multiple sewings.

Table 1 shows the computational time for the simulation test of a jacket. Tests were performed on a PC PentiumIV 2.66 GHz processor, 512 Mb RAM. About 75% of the computational time was spent on detection of collisions between jacket's grid entities and mannequin's. To get faster computations, optimized collision detection [VM00] and implicit ODE solvers [HEE*02] are under development.

5.2. Design of Car's Soft Tops

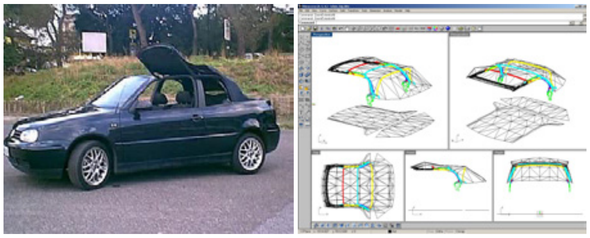
To test the system with functional simulation tasks in other industrial contexts, another problem was analysed: the modelling and simulation of a car's soft top for automotive design applications. The task was developed in the framework of the Brite-Euram project *DMU-FS* (*Digital Mock-Up for Functional Simulation for Product Conception and Down-Stream Processes*), aiming at developing methodologies and software tools for the simulation of product functionalities within a digital mock-up, in collaboration with several car companies and CAD developers.

In this case, Softworld data were integrated with the commercial system for discrete dynamic analysis DADS, by LMS International (*www.lmsintl.com*), to simulate the folding fabric of a sunroof in a Volkswagen Golf Cabrio car (Figure 8.a). We briefly describe the two phases of geometric modelling and physics-based simulation of the sunroof.

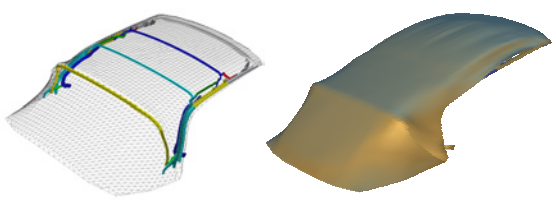
Sunroof modelling. The closure mechanism of the sunroof was modelled using Rhinoceros, by Robert McNeel & Associates (*www.rhino3d.com*), while sunroof panels were designed from PMU (Physical Mock-Up) models provided by Karmann GmbH (*www.karmann.com*) (Figure 8.b). The 2D panels were discretized with particle grids, using a multi-layered fabric composition. Sunroof's structural fabrics present, in fact, two external layers of ordinary cloth and an internal rubber film. The soft car's top was then located in 3D by constraining its border to the articulated frame. 3D placement of the soft car's top against the frame was obtained by using data provided by Karmann. Figure 8.c shows the associated particle-based model for the closed soft top's configuration.

Panel simulation. A first simulation returned the panel configuration in static equilibrium with flat, motionless sunroof frame, to be used as an initial configuration (Figure 8.c) for the second simulation, describing the sunroof opening. Both off-line and integrated simulations could be performed. In the first case, discrete trajectory values of the rigid arms were pre-computed and passed to our simulation module at discrete time steps as position constraints for panel's border particles. In the second case, interchange data functions were passed through sockets from DADS to Softworld. Figure 9 shows some simulation steps of the opening phase.

Reliable results were obtained even in this case with moving rigid parts. The computational time for the dynamic simulation of the car's top is shown in Table 2. Tests were performed on a PC AMD Athlon XP 1.8+ GHz processor, 256 Mb RAM. The computational time was significantly lower than in the jacket's case, as many fewer collisions occurred between the soft top and the articulated frame. In this case the main difficulty was rather guaranteeing a proper KES-F measure of sunroof's textile properties, here estimated by extrapolation, as the component textiles were not included in the original KES-F list of fabrics.



(a) Real object (b) CAD model



(c) Particle-based model: static simulation

Figure 8: *Geometric and particle-based modelling of a car's soft top.*

Number of particles	2600
Number of triangles	4481
Number of rigid body points	5064
Number of rigid body triangles	3766
Time Step (ODE solver)	1.0e-4
Computation Time	44' to simulate 1 sec

Table 2: *Computational times for car soft top's simulation.*

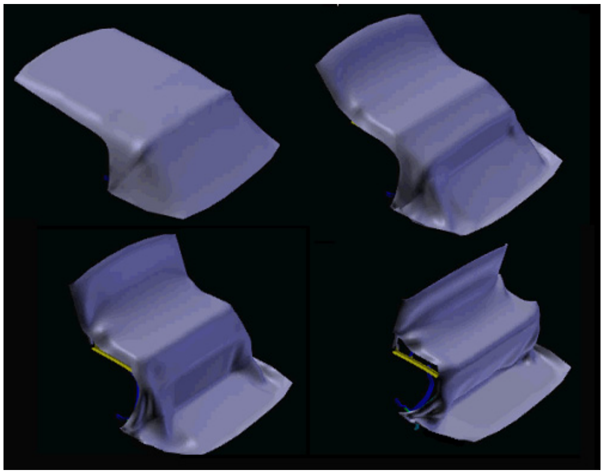


Figure 9: *Dynamic simulation of the physics-based car's soft top model during the opening phase of the mechanism.*

6. Conclusions and Future Work

A CAD-oriented approach was proposed for the virtual design and prototyping of functional cloth, such as apparel and industrial textiles. Differently from animation systems, which focus on regular-shaped one-layered cloth models, we considered design aspects necessary for real cloth production, analysing textile configurations as results of assembled parts, seams, layers and other construction constraints. The system includes 3D physical simulation for accurate shape prediction, based on a Newtonian particle model extended to complex multi-layered cloth. KES-F data were considered to simulate the different material behaviour. As applications, several cases of industrial interest were modelled and simulated. For the clothing sector, garments on mannequins were considered and, for the automotive sector, functional fabrics such as soft car's tops in dynamic conditions.

Work is currently in progress to expand the geometric modelling capabilities of the system and specialize them to the textile context, e.g. computer emulation of tight/loose seams and manufacturing effects (e.g., pressing, pleat generation, starching, etc.). Efforts are currently under way to improve simulation performances and reduce the computational time, by considering optimized collision detection techniques and efficient implicit ODE solvers, e.g. [HEE*02].

Acknowledgements

This work was supported by the Brite-Euram project DMU-FS, and the projects TA2000 and ViCloth, funded by the italian ministry MIUR. We thank Ing. Matteo Benassi, from Politecnico di Milano, for activity on the sunroof model.

References

[Ao90] Aono M.: A Wrinkle Propagation Model for Cloth. *Proc. Computer Graphics International* (*CGI '90*), 1990, 95-115.

[ABW01] Aono M., Breen D.E., Wozny M.J.: Modeling Methods for the Design of 3D Broadcloth Composite Parts. *Computer-Aided Design*, vol. 33 (13), 2001, 989-1007.

[BW98] Baraff D., Witkin A.: Large Steps in Cloth Simulation. *Computer Graphics* (*Proc. SIGGRAPH '98*), 1998, 43-54.

[BB88] Barzel R., Barr A.H.: A Modeling System based on Dynamic Constraints. *Computer Graphics* (*Proc. SIGGRAPH '88*), vol. 22 (4), 1988, 179-188.

[BGR00] Bonte T., Galimberti A., Rizzi C.: A 3D graphic environment to design garments. In *From Geometric Modeling to Shape Modeling*. Eds. Cugini U., Wozny M. Kluwer Academic Publishers, 2000, 137-150.

[BHW94] Breen D.E., House D.H, Wozny M.J.: Predicting the Drape of Woven Cloth using Interacting Particles. *Computer Graphics* (*Proc. SIGGRAPH '94*), vol. 28 (4), 1994, 365-372.

[BFA02] Bridson R., Fedkiw R., Anderson J.: Robust Treatment of Collision, Contact and Friction for Cloth Animation. *Computer Graphics* (*Proc. SIGGRAPH '02*), vol. 21 (3), 2002, 594-603.

[BMF03] Bridson R., Marino S., Fedkiw R.: Simulation of Clothing with Folds and Wrinkles. *Proc. ACM SIGGRAPH Eurographics Symposium on Computer Animation* (*SCA '03*), D. Breen and M. Lin Eds., 2003, 28-36.

[CK02] Choi K.J., Ko H.S.: Stable but Responsive Cloth. *Computer Graphics* (*Proc. SIGGRAPH '02*), vol. 21 (3), 2002, 604-611.

[DGR00] Dias J.M.S., Gamito M.N., Rebordao J.M.: A Discretized Linear Elastic Model for Cloth Buckling and Drape. *Textile Research Journal*, vol. 70 (4), 2000, 285-297.

[EW96] Eberhardt B., Weber A.: A Fast Flexible, Particle-System Model for Cloth Draping. In *Computer Graphics in Textiles and Apparel*, *IEEE Computer Graphics and Applications*, vol. 16 (5), 1996, 52-59.

[EDC96] Eischen J.W., Deng S., Clapp T.G.: Finite Element Modeling and Control of Flexible Fabric Parts. In *Computer Graphics in Textiles and Apparel*, *IEEE Computer Graphics and Applications*, vol. 16 (5), 1996, 71-80.

[Fey86] Feynman C.R.: Modelling the Appearance of Cloth. *MSc Thesis*. Dept. of Electrical Engineering and Computer Science, Massachussetts Institute of Technology, US, 1986.

[FRC03] Fontana M., Rizzi C., Cugini U.: A Graphical User Interface for the Physics-based Modelling and Simulation of 2D Deformable Objects. *Proc. Eurographics Italian Chapter '03*, Milano, 2003.

[Gal01] Galimberti A.: Sviluppo di un sistema di simulazione per la progettazione di capi di abbigliamento. *Ph.D. Thesis*. Dipartimento di Ingegneria Industriale, Università di Parma, Italy, 2001.

[HEE*02] Hauth M., Etzmuß O., Eberhardt B., Sarlette R., Sattler M., Daubert K., Kautz J.: Cloth Animation and Rendering. *Eurographics '02 Tutorial* , 2002.

[HB00] House D.H., Breen D.E., Eds.: *Cloth Modelling and Animation*. A K Peters Ltd., Natick, MA (US), 2000.

[Kaw80] Kawabata S.: *The Standardization and Analysis of Hand Evaluation.* Textile Machinery Society of Japan, Osaka, 1980.

[LDG96] Li L., Damoran M., Gay R.K.: Aerodynamic Force Models for Animating Cloth Motion in Air Flow. *The Visual Computer*, vol. 12 (2), 1996, 84-104.

[NG96] Ng H.N., Grimsdale R.L.: Computer Graphics techniques for modelling cloth. In *Computer Graphics in Textiles and Apparel*, *IEEE Computer Graphics and Applications*, Eds. Breen D.E., vol. 16 (5), 1996, 28-41.

[OIT*92] Okabe H., Imaoka H., Tomiha T., Niwaya H.: Three Dimensional Apparel CAD System. *Computer Graphics* (*Proc. SIGGRAPH '92*), vol. 26 (2), 1992, 105-110.

[Pro97] Provot X.: Collision and Self-collision Handling in Cloth Model Dedicated to Design Garments. *Proc. Graphics Interface '97*, 1997, 177-189.

[TPB*87] Terzopoulos D., Platt J., Barr A.H., Fleischer K.: Elastically Deformable Models. *Computer Graphics* (*Proc. SIGGRAPH '87*), vol. 21 (4), 1987, 205-214.

[TL94] Turk G., Levoy M.: Zippered Polygonal Meshes from Range Images. *Computer Graphics* (*Proc. SIGGRAPH '94*), 1994, 311-318.

[Van98] Van Gelder A.: Approximate Simulation of Elastic Membranes by Triangulated Spring Meshes. *Journal of Graphics Tools*, vol. 3 (2), 1998, 21-41.

[VM00] Volino P., Magnenat-Thalmann N.: *Virtual Clothing. Theory and Practise*. Springer-Verlag, Heidelberg, 2000.