Towards Virtual Prototyping of Complex-shaped Multi-layered Apparel

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ABSTRACT

Virtual prototyping of cloth has recently become a topic of increasing interest both in computer graphics and computer-aided design for industrial fabric or apparel production. Aiming at an accurate simulation of garment shapes, this paper presents a physics-based system for virtual cloth modelling, specifically conceived for design purposes and targeted to the clothing industry. This environment should allow the designer/modellist to validate her/his style and design options through the analysis of garment virtual prototypes and simulation results in order to reduce the number and role of physical prototypes. To this end, a complete physics-based model has been defined, oriented to actual complex-shaped apparel, incorporating aspects related to garment's shape and structure (e.g., 2D profiles of basic patterns and multi-layered parts), mechanical/structural properties of fabric materials and multi-layered parts, and design/manufacturing processes (e.g., ironing, starching). The physical garment's model has been developed upon a particle-based model embedded in constrained Newtonian dynamics with collision management. The system has been validated within European and national projects, simulating several female and male garments with different levels of design complexities and directly provided from involved clothing companies.

Keywords: garment design and manufacturing, garment simulation, physics based-models.

1. INTRODUCTION

Cloth modelling has progressively become a topic of large investigation in computer science. Since the early '90s, scientific and commercial communities have developed several cloth modelling systems having in minds different points of view and goals. Basically, two main categories of software products can be distinguished: i) for cloth *visualization* and ii) for cloth *design*. Software systems for cloth visualization aim at producing images that look real for computer animation applications, while systems for garment design focus on the definition and construction of functional cloth shapes for real manufacture (e.g., clothing, upholstery, etc.).

As concerns the clothing sector, several 2D CAD systems can be found on the market for pattern drafting, sizing, nesting, and marker making, together with CAM modules for cutting/sewing. Nevertheless, apparel companies claim the lack of effective garment-oriented CAD packages to design directly in 3D and provide the modellist with tools for 3D shape modelling and analysis of cloth behaviour. Most of the existing commercial CAD systems, on the contrary, still rely on mere 2D geometrical modelling and do not provide virtual simulation tools (with few exceptions, e.g., the *DressingSim* module used by Investronica Sistemas [13]).

To be able to reproduce garments' actual behaviour, systems require an underlying physic-based modelling core, taking into account not only garment's geometry but also fabrics' mechanical properties and interactions with an external environment.

In this paper we concentrate our attention on methodologies and applications related to garment design. In particular, we present a CAD-oriented physics-based system for virtual cloth simulation, expressly conceived for real design purposes, differently from other research prototypes or systems currently available on the market mainly oriented to visualization for movies, or virtual catwalks (e.g., *TopixCloth,* plug-in for *Softimage V3.7* from Topix [18], or *MayaCloth,* plug-in for Maya from Alias [15]). The goal has been to develop an environment assisting the designer, to validate his/her style and design options through the analysis of garment virtual prototypes and simulation results, in order to reduce the number and role of physical prototypes.

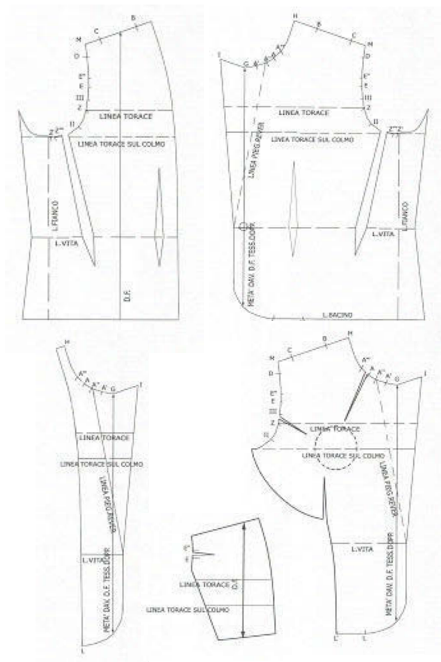

Fig. 1. A man's jacket: geometry of some 2D front panels.

2. MODELLING ISSUES RELATED TO GARMENT DESIGN AND MANUFACTURING

In the effort of getting closer to cloth manufacturers' needs, we have developed a tool to assist the designer/modellist throughout the cloth design process, managing aspects related to the various garments' structural parts (e.g., shoulder paddings, collars) and to manufacturing processes that influence the final garment shape. To this end, in collaboration with Italian and European clothing companies[1], a preliminary study was carried out, devoted to the analysis of garment's structure and related development process, from the conceptual design phase up to product ready for purchase.

Several levels of design complexities have to be considered while defining shape, assembly rules and aesthetic/functional details of real tailored garments. A man's jacket, for instance, is a particularly elaborated garment. It is manufactured from a large number of 2D panels with complex-shaped borders connected with each other by means of various darts and single/multiple seams. Besides, jacket's final volume strongly depends on a multi-layered structure obtained by overlapping different types of fabric materials (cotton, canvas, linen, horsehair, etc.).

Stuffings for shoulders are placed to define shape proportions along horizontal directions. Further aesthetic and functional features enrich the structure of the jacket, e.g., buttons, hooks, external and internal pockets and other finishings. Moreover, jacket's final smooth or sculptured volume is reached by starching, pleating, ironing, and other mechanical/chemical operations that induce permanent or semi-permanent deformations on jacket's fabrics. As an example, Fig. 1 shows 2D panels composing a jacket's front part, while Fig. 2 displays its multi-layered structure with specification of sewing lines.

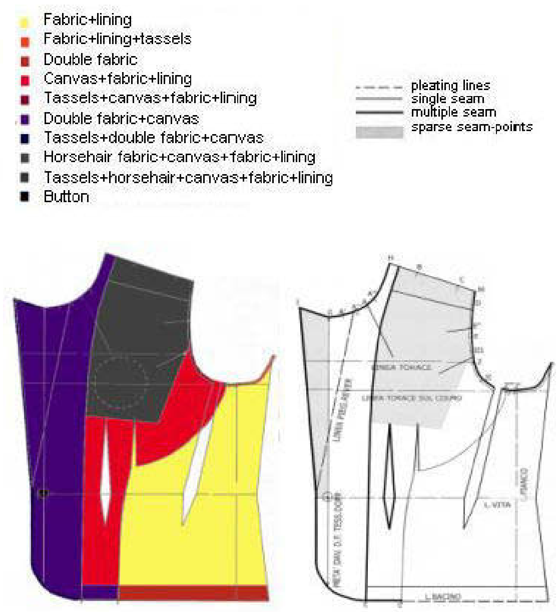

Fig. 2. Structure of jacket's front panel: 2D patterns with specification of fabric structural parts, seams, darts and pleats.

By this example, therefore, we can realize the difficulty of a computerized reconstruction of a real complete garment, which could take into account all these complex design and manufacturing effects.

The related product development process can be schematized as a *3D-to-2D-to-3D* process. Procedurally, a specific sequence of design/ manufacturing steps has to be considered, involving aspects such as:

- definition of a reference 3D shape;
- definition/extraction of 2D panels (2D models);
- definition of assembly rules (seams, darts, overlapped layers, buttons, etc.);
- definition of materials;

[1] F.lli Corneliani, garment manufacturer, team coordinator of the italian TA2000 Consortium, and Confecciones Mayoral (ES), GFT Donna (IT), garment manufacturers cooperating in the framework of the Brite-Euram MASCOT project [7].

- cut of 2D fabrics (single layers);
- assembly of fabrics by layer overlapping;
- assembly of one- or multi-layered fabrics along border parts (seams, darts, etc.);
- mechanical/chemical post-treatment of textiles by shape deformation (pleats, ironing, etc.);
- 3D configuration/placement over supports or external objects (e.g., mannequins);
- analysis of the final garment's shape and behaviour in the 3D physical space.

The analysis of garment design and related manufacturing processes lead us to the definition of a physics-based model for real apparel that incorporates most of the above construction steps (Section 3), from early 2D panel definition up to final 3D model for assembled multi-layered apparel. In our methodology, we progressively incorporate within our garment's model three main cloth's characteristics:

- *Shape and structure,* i.e. geometrical description of garments and relation among parts (e.g., 2D profiles of basic panels and multi-layered parts);
- *Material,* i.e. mechanical/physical properties (e.g. KES or FAST measurements of fabric types and multi-layered parts);
- *Process,* i.e. design and manufacturing processes (e.g., ironing, starching).

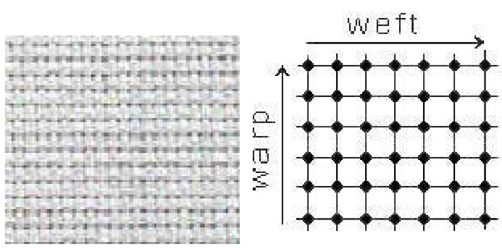

Fig. 3. Particle-based model of a woven fabric.

3. DEFINITION OF THE 3D GARMENT PHYSICS-BASED MODEL

A key issue is the choice of a proper underlying mathematical model for cloth, capable to accurately represent its shape and behaviour. Several cloth models can be found in the computer graphics literature, based on different *geometrical, physics-based* or *hybrid* approaches. For a general overview on cloth modelling, see [4,12,19,10]. Although some approaches give very accurate results [5,19], most of the proposed models refer to simple regular-shaped cloth layers or very basic, already assembled, garment shapes.

The above literature suggests that physics-based models, in particular *discrete* approaches [11,17,19,1,5,10], seem to be the more adequate solution for representing highly deformable materials such as textiles. In discrete physics-based approaches, cloth objects are modelled as systems composed of a finite number of mechanical constitutive elements subjected to certain static/dynamic laws. In our work we adopted the so-called *particle-based* model [11,17]. In this approach, constitutive elements are particles with mass, subjected to internal and external forces, subjected to Newtonian dynamics (*force-based* formulation), or assuming certain potential energies, e.g. Lagrangian formulations (or other *energy-based* approaches). Particle-based cloth models tend to represent more efficiently the highly flexible behaviour of cloth and its characteristic "discrete" structure as a woven or knitted (or, in some cases, unorganized) plot of interlaced threads (Fig. 3).

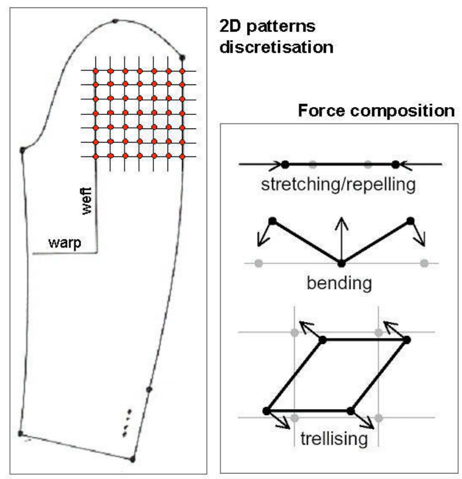

Fig. 4. Particle grid associated to fabric panels and internal force characterization.

3.1 Particle-based Characterization of 2D Panels

Single fabric pieces are analyzed, as they represent the basic garment model's components. *Woven* textiles are considered with threads interlaced according to orthogonal warp and weft directions (Fig. 3). Fabric's flattened pieces are assumed to have a negligible thickness and are defined as open connected and bounded figures $F \subseteq R^2$ with piecewise regular boundary ∂F (e.g. a closed loop of linear or curved edges). Similarly to Breen's and Provot's models [11, 17], we associate a particle-based model to each fabric panel by defining a structured 2D grid with coordinate lines along warp and weft directions. Interior particles correspond to grid nodes, located at warp/weft thread intersections, while boundary particles are defined from intersection of grid lines with the fabric border (Fig. 4).

Differently from Breen's energy-based method, we here use a Newtonian force-based approach, as it can include more general dynamic problems where parts can be in motion. Panel's grid topology characterizes the internal discrete force distribution, computed as linear or torsional springs connecting neighboring particles. Taking into account the woven structure of threads, we consider (Fig. 4):

- *stretching/repelling* forces, acting to keep particles at rest distance (modelled as Kelvin visco-elastic springs directed along weft and warp);
- *bending* forces, acting out-of-plane to keep objects flat (derived by torsional moments normal to their support surface);
- *trellising* (or *shear*) forces, acting to contrast any possible deformation of the rectangular cells (modelled again through torsional moments normal to the cells).

Internal force values are estimated from global mechanical data for textiles, measured by the Kawabata Evaluation System (KES) [14]. Details about internal force computation can be found in [9].

3.2 From 2D Panels to Assembled Garments

A garment is the complex-shaped result of assembled components. Thus, geometrical abstraction helps us in defining a full garment shape as a non-manifold entity

$$G = \bigcup_{i=1..n_F} F'_i \cup \bigcup_{i=1..n_A} A_i \qquad (1)$$

where F'_i are fabric layers in a spatial configuration (2D manifolds in R^3) deformed from original flat panels $F_i \subseteq R^2$, for $i = 1,2,...,n_F$, and $A_i \subseteq R^3$ are geometries of rigid or soft accessories, for $i = 1,2,...,n_A$. When existing, the latter are generally few small entities, such as buttons, hooks, zips, paddings, etc. Fabric layers are sewn with each other along portions of their boundary, or can be partially or totally attached in interior sub-regions with other layers (as it occurs in multi-layered parts as shown in Fig. 2).

Under these premises, after particle grid discretization of single fabric layers, we need to consider further steps to generate a complete physics-based model for garment simulation. On this regard, we define proper algorithms that locally modify/upgrade the geometry and topology of cloth's particle meshes, with corresponding physical discrete parameters (e.g., particle masses and internal force distribution) in order to emulate the following design steps: (a) sewing of 2D fabric panels; (b) insertion of darts; (c) fabric layer overlapping; (d) insertion of buttons and hooks; (e) placement of the full garment model in a 3D space configuration (e.g. on a mannequin).

3.2.1 Sewing of 2D Panels

For 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 garment manufacturing. In future, however, we will consider also multiple sewings, involving more than two components at a time.

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 connected pairwise 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 particle resolution different between one panel and the other, or in case of complex-shaped borders. Fig. 5 shows a sewing process between two particle grids of fabric panels.

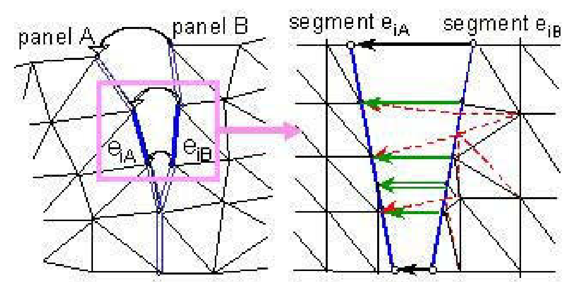

Fig. 5. Sewing process between two fabric panels: (1) seam definition as mapping 1 to 1 between vertices of panel borders; (2) detail of the sewing process over a single segment pair.

Dart insertion is again a sewing operation, as darts can be regarded as special seams along a fixed sequence of edges, between a panel and itself. In other words, one (or more) vertex(vertices) is (are) sewn with another (other) vertex(vertices) belonging to boundary loops of the same panel.

3.2.2 Other Construction Processes

Structured Multi-layered Parts

An algorithm for *layer overlapping* has been considered to update the original cloth particle-based grid in order to model the presence of possible fabric layers placed on top of each other, as in case of paddings and linings. To this aim, we change physics-based properties (masses, springs, bending and trellising forces) corresponding to particles and edges inside specified sub-regions of the main panels, substituting them with proper values including all effects of single added layers, with their specified materials, through the effect of a unique equivalent material (e.g. mass summation, equivalent constants in parallel spring networks, etc.)

Insertion of Buttons and Hooks

The effect of buttons and hooks intervenes when two panels to be connected are sufficiently close to each other. Each virtual button is simulated by connecting the two grid points closest to the required button position and imposing significantly hard spring force and mass increment.

3D Garment's Placement

Once the particle-based model of the garment is assembled with all its components, the corresponding *garment's placement in 3D* has to be defined. 3D particles' configuration is arranged by considering the presence of external rigid objects in the scene (e.g., mannequins or rigid supports) and according to mapping laws from 2D onto 3D, respecting local isometries in grid triangles/edges. Note that the 3D placement of the garment onto the rigid support can be chosen with a certain (relatively small) offset distance from rigid supports.

The final accurate 3D placement of the garment model onto the support will be scope for the physical simulation phase.

Fig. 6. Particle-based models of different types of garments and subdivision into regions.

Fig. 6 shows some examples of female and male garments, displaying the component 2D panels for skirts and a jacket, assembled and placed around the virtual mannnequin. In the last example, a subdivision in subregions has been highlighted to specify the different behaviour of jacket's structural parts.

4. DYNAMIC SIMULATION

The complete particle-based model of a garment is defined by a system $S = \{P_i : i = 1,..,N\}$ of N particles, having masses m_i, positions $\mathbf{r}_i$ and velocities $\mathbf{v}_i = \dot{\mathbf{r}}_i$, for $i = 1,2..,N$. The configuration of particles is assigned at an initial time t_0, by known positions $\{\mathbf{r}_{i0}\}$ and velocities $\{\mathbf{v}_{i0}\}$, $i = 1,..,N$.

The simulation is carried out using Newton's law $\mathbf{F} = m\mathbf{a}$, applied to a particle system. The resulting mathematical model is an initial value second order ODE system of 3N equations and 3N unknowns, i.e. positions $\{\mathbf{r}_i\}$, $i = 1,..,N$, that can be reduced to a first order system of 6N equations, numerically solved by time discretization [17,10]. However, to simulate the behaviour of a garment it is not sufficient to consider only internal forces; we need also to manage interactions between the object and the surrounding environment. We have taken into consideration:

- *external forces,* such as gravity, wind and viscous forces, added to the internal forces;
- *constraints,* i.e. conditions restricting the movements of cloth parts or rigid objects;
- *collisions* with obstacles, and *self-collisions* among cloth parts.

Bilateral constraints are considered, expressed as algebraic equations $c_i(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_N, t) = 0$, for $i = 1,2, ..., r$ (r number of constraints). Among the several methods for constraint management (e.g., *penalty method*, *rate-controlled constraints*, *Lagrange multipliers* and *dynamic constraints* [2,16]), the dynamic constraint method has been here considered, since it permits to apply multiple constraints to the same particle and ensures the respect of all the constraints at each step of the simulation. The approach is an extension of a generalized Lagrange multipliers' method, returning an algebraic system at each time step, whose solution gives reactive forces, to be added to active internal and external forces [8].

To complete the analysis of the interactions with the surrounding environment, also possible collisions are taken into account. They occur, for instance, when parts of flexible objects (e.g., garments) hit some rigid objects (e.g., mannequins) or penetrate towards each other (self-collisions). Collision management involves two aspects: *collision detection* and *collision response*.

Collision detection plays a significant part in the total computational time of simulations (up to 80%). Among several techniques for collision detection, e.g., *voxel subdivision, octree subdivision, bounding box hierarchy, proximity tracking*, and *curvature–based* methods [17,19,10], aligned axis bounding box (AABB) hierarchies with region subdivision have been adopted, as a good compromise between simplicity and efficiency.

In the *collision response* phase, the velocities of particles belonging to colliding entities are modified due to elastic/inelastic bouncing off. The corresponding velocity variations due to collisions are computed as solution of a linear system, by handling collisions as unsatisfied scalar unilateral constraints $d_i(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_N, t) < 0$, for $i = 1, 2, ..., s$, where s is the number of collisions at a certain time, and using again the dynamic constraint approach [8].

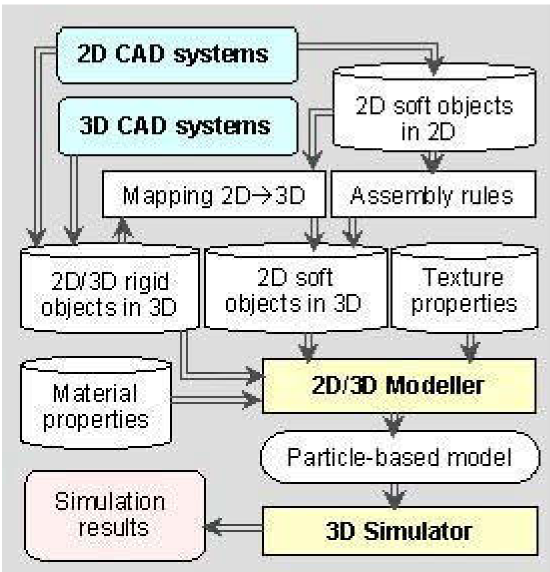

Fig. 7. SoftWorld's architecture.

5. SOFTWORLD: SYSTEM FOR PHYSICS-BASED MODELLING AND SIMULATION

The particle-based model previously described has been implemented in a system named *SoftWorld2.0*, running on Windows, Unix/Linux, SGI-IRIX platforms. Fig. 7 displays the overall SoftWorld's architecture. Grouping together the several implemented procedures by scope, we can distinguish two fundamental modules:

- *2D/3D Modeller*, to create the physics-based model associated to the 3D configuration of the garment. It generates the particle-based grid of all 2D panels, sewing and assembling them over the mannequin, to create the initial 3D configuration ready for garment simulation (Section 3).
- *3D Simulator*, to reproduce actual cloth behaviour with simulation based on constrained Newtonian dynamics with collision management (Section 4).

The system is provided with a Graphical User Interface, to create a unique environment from which both the Modeller and the Simulator are executed. Tab. 1 displays input and output data of the 2D/3D Modeller, while Tab. 2 describes the main algorithm in the 3D Simulator.

2D/3D Modeller

Input data

(a) Material properties (e.g., KES data for fabrics)
(b) Rigid bodies (e.g., mannequins, frames)
(c) Geometry of 2D panels (for extended version with full 3D soft modeling tools: geometry of 3D soft shapes)
(d) Rules for 2D→3D mapping
(e) Model construction constraints (e.g. textile operations: seams, darts, fabric layers, buttons)
(f) (If any) dynamic constraints (kinematics of rigid parts)

Output data

(a) Physics-based information about soft objects (particle 3D positions, masses, associated grid, internal/external forces, geometric/kinematic constraints)
(b) Physics-based information about rigid parts (3D point positions, the associated grid, geometric/kinematic constraints)

Tab. 1. Input and output data of the 2D/3D Modeller.

3D Simulator

Known configuration $\{\mathbf{r}_i(t_0), \mathbf{v}_i(t_0)\}$, for $i = 1, 2, ..., N$

For step $k = 1, 2, ..., n$:

(1) It computes the active forces $\mathbf{F}_i^{(a)}(t_k)$ (from internal and external contributions) on each particle i;
(2) estimates the effect of bilateral constraints by computing equivalent reactive forces $\mathbf{F}_i^{(r)}(t_k)$ for each i;
(3) computes the new velocities $\mathbf{v}_i(t_k)$ from numerical solution of Newton's law (ODE solver, 1st part);
(4) detects the colliding particles;
(5) updates velocities $\mathbf{v}_i(t_k)$ with $\mathbf{v}_i(t_k) + \Delta\mathbf{v}_i$ for the colliding particles, from velocity variation of collision response algorithm (linear system solution), with $\Delta\mathbf{v}_i = 0$ for non-colliding particles;
(6) computes the new particle positions $\mathbf{r}_i(t_k)$ from ODE solver, 2nd part.

Tab. 2. Main algorithm of the 3D Simulator.

6. INDUSTRIAL TEST CASES

Several tests were done to evaluate our cloth design and simulation approach using SoftWorld2.0. As we were interested in real complex-shaped apparel, the analysis and simulation of garment examples were carried out starting from initial geometrical 2D and 3D models directly provided by clothing companies.

Tests were performed for both male and female clothing within the framework of two research projects, the Brite-Euram MASCOT [3] and the Italian TA2000 [6] projects, in cooperation with industrial partners from the clothing industry (see note [1]), and CAD/CAM developers[2]. Although based on the same modelling and simulation algorithms, the two ways of proceeding while defining male and female clothes were quite different.

6.1 Women's Garments

Experimentation on 3D garment design for woman's clothing was carried out within the MASCOT project. The main goal was to develop a 3D graphical environment for industrial applications in the clothing industry, to permit the design of woman base garments in 3D, style evaluations by comparing different types of fabrics, and the automatic generation of the 2D panels starting from the 3D representation. SoftWorld was integrated with a geometric 3D garment modeller, based on surface representation by NURBS and developed at the University of Valenciennes [3].

In this case, 2D panels with all information (e.g., sewing lines), necessary to the Simulator for their correct location on virtual mannequins, were directly derived from the garment 3D model.

Once generated the 2D panels from the geometric 3D modeller, our 2D/3D Modeller (Tab. 1) generates the particle-based grid of each 2D panel associating proper KES data corresponding to the chosen fabric materials. By using information provided by the geometric modeller, 2D panels were sewn and located properly on the mannequin for the final simulation of its behaviour under static conditions.

To generate the physics-based model, the following basic assumptions were made:

- use of a simplified model representing the fabric as composed of a single equivalent layer;
- generation of a final configuration in 3D depending on the 2D geometry of patterns but also on intrinsic mechanical properties due to the considered type of fabric (e.g., cotton, linen, silk, etc.);
- choice of KES measurements to characterize fabric's mechanical behaviour;
- use of geometric information at several levels, e.g. to define 2D patterns profiles, and functional or aesthetic details such as the location of seams, darts, buttons and other constraints.

Fig. 8 portrays the particle-based model of a woman's dress before simulation and corresponding simulation results. Fig. 9 displays the simulation of a woman's top.

[2] Lectra Systemes (FR), Investronica Sistemas (ES), and TELMAT (FR), in the framework of MASCOT project.

The simulated female garments were not particularly elaborated; yet, they permitted us to validate the adopted approach with end-users participating to the project. At this stage, comparisons between physical prototypes and simulated garments were made at a qualitative level.

Fig. 8. Particle-based model and simulation of a woman's dress.

Fig. 9. A simulated woman's top.

6.2 Men's Garments

Further experimentation was carried out, targeted to the design of man's apparel, developed in the framework of TA2000. Together with the technical staff of F.lli Corneliani company (manufacturer of male garments), we chose elaborated jacket models, to properly validate our 2D/3D Modeller and 3D Simulator on more complex-shaped clothing of real interest.

The design process currently followed by the clothing companies was first carefully analysed to extrapolate useful functionalities for the geometric modelling phase. Typically, the designer defines a new style by modifying the shape of a physical prototype, e.g., changing the length of the sleeves or tightening the waist, according to fashion trends and stylist's ideas. To do this, the designer uses reference elements such as sewing lines or significant and structural elements (e.g., waist or shoulders, etc.). A modelling system should permit the designer to operate in the same way, using a digital prototype instead of a physical one.

Thus, an *editor module* was implemented by using and combining MAYA *Deformers* [15], to enable the user to change the shape of a reference jacket's geometric model provided by F.lli Corneliani. From the analysis of modellist's modus operandi, we identified and implemented a set of shape modifiers emulating traditional modifications on garment's parts, such as "shorten/lengthen sleeves", "tighten/enlarge shoulders", "tighten/enlarge waist", "shorten/lengthen whole jacket". An *export module* was developed to automatically generate a file, containing information about the modified 3D geometric model, to be used as input for 2D panel extraction. The generation of 2D panels was done by means of a commercial 2D CAD package used at F.lli Corneliani site.

The 3D Simulator could generate the particle-based grids of the panels, then assembled together and placed on a virtual mannequin thanks to the 2D→3D mapping rules stored by the 2D/3D Modeller. Once the complete particle-based model was created in 3D, simulation could be performed. Fig. 10 displays the main steps of the jacket's design procedure.

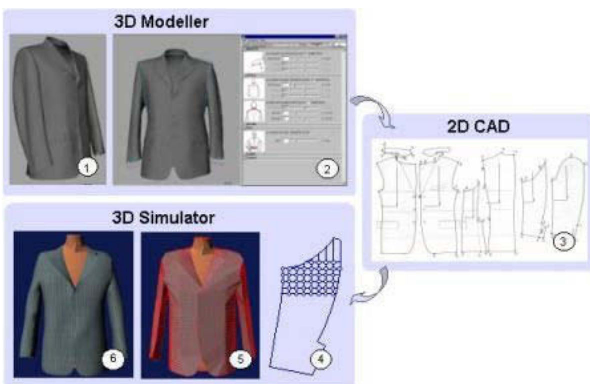

Fig. 10. Virtual design of male garments. Main steps: (1) Selection of a base jacket. (2) Geometrical modification of jacket's parts. (3) Generation of 2D patterns. (4) Particle-based model of each panel. (5) Panel assembly with final particle-based model ready for 3D simulation. (6) Simulation results.

Regarding simulation, the assumptions made for female apparel are not sufficient for men's jackets. In fact, as explained in Section 2, a jacket has a very complex structure. Its final shape is obtained by overlapping different types of material and by resorting to particular manufacturing processes inducing permanent local deformation (e.g. by ironing, starching, and special tight-loose sewings). Therefore, the garment's physical model was enriched as follows:

- 2D panels were subdivided into sub-regions, each corresponding to a structural part of the jacket, e.g., shoulder, facing, collar, etc. Each region was characterized by different physical parameters, to manage the fabric overlapping and to integrate the above-mentioned manufacturing effects (see jacket model in Fig. 6).
- Further parameters were introduced in order to amplify/reduce the effect of permanent material deformations (e.g., lapel pleat) obtained by means of manufacturing processes, such as ironing.

Fig. 11 shows the 2D panel corresponding to the right front of the jacket and related sub-regions identified together with the modellists: (A) shoulder, (B) pleating line of the lapel, (C) facing, and (D) bottom of the jacket.

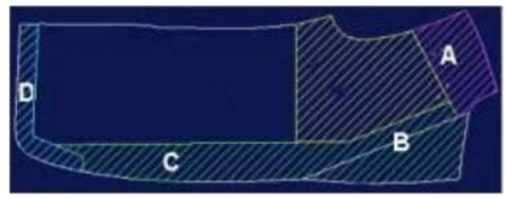

Fig. 11. Right front 2D panel and related sub-regions.

A stand-alone simulator, named *TextileLab*, was implemented to allow the designer to interactively modify mechanical parameters associated to each region, and execute garment simulation. In collaboration with project's end-users, a set of simulation tests was performed for each region, varying associated parameters by means of multiplicative factors, and using KES measurements as basic values. This permitted us to characterize each single region, reaching simulation results judged good enough by cloth designers and manufactures.

The main goal of this experimentation phase was to verify the feasibility of our approach (jacket subdivision into regions). We systematically analysed the regions, starting from those with more problems:

- *collar* and *lapel,* to better characterize pleats;
- *arm-hole*, to make it uniform;
- *front* and *back parts*, to control the global volume effect;
- *sleeve*, to control the bending effect;
- *bottom* of the jacket, to include facing and flattening effects due to ironing and pressing.

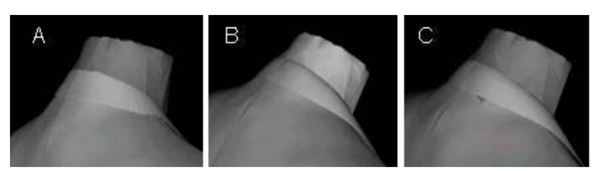

Fig. 12. Simulation results: collar region.

Fig. 12 shows some progressive improvements on simulation results obtained around the *collar* region. In the earliest result of Fig. 12(A) the collar was too flat, while in Fig. 12(B-C) the behaviour appears more correct, coherently with the real situation, with increased volume effects. In these cases, we changed parameters associated to the collar region, such as pleat bending parameters. Fig. 13 shows the more recent simulation results obtained for a jacket leaned on the bust of a mannequin in static conditions, with some texturized details shown in Fig. 14.

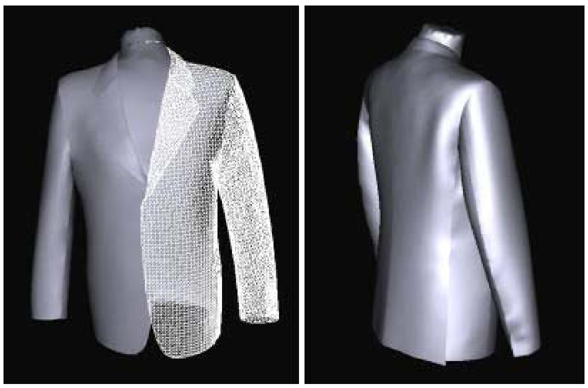

Fig. 13. Simulated jacket.

Fig. 14. Some details of a simulated jacket.

7. CONCLUSIONS AND FUTURE WORK

In this paper, a physics-based model for apparel has been presented, derived from a discrete particle-based model and enriched with algorithms considering garment shape and structure (e.g., 2D profiles of basic patterns and multi-layered parts), fabrics' mechanical properties, and design and manufacturing processes (e.g., ironing, starching). A system has been implemented upon such physic-based model, named SoftWorld. The system includes specific algorithms for textile operations such as sewing, button and dart insertion, etc. and has been integrated within CAD environments for cloth design.

Applications and examples on simulated test cases for the design of men's and women's garments, directly provided by clothing companies, have been shown. The results of tests carried out with the end-users are encouraging and prove the validity of our approach. We envisage the need to execute further KES measurements on specimens of jacket's structural parts (e.g., fabric reinforced with lining), in order to get increasingly accurate results.

Work is currently in progress for expanding the geometric modelling capabilities of the system and specializing 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 computation time, by considering optimization techniques for collision detection and efficient implicit and semi-implicit ODE solvers for the numerical solution of Newtonian particle systems associated to garment configurations [10].

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