Abstract

Cloth simulation and fabric measurement are tightly linked areas of research. In order to obtain high quality animations of dressed models, the properties of the simulated garment must first be evaluated in an accurate and adapted way. As cloth is a very complex, isotropic material, the evaluation of its properties is difficult to achieve, and various approaches exist. Depending on the design of the simulation engine, the measurements will be done differently, so that the outputted parameters match the inputs required by the simulator. Various issues must be considered, and depending on the complexity of the simulated garments, tradeoffs must be made in order to reconcile the real features of the cloth (stitches, layers...) and the computational capacities of the simulator (numerical integration, collision detection...)

Keywords: Fabric measurement, cloth simulation, computer animation.

1. Introduction

Fabrics are complex visco-elastic materials. They must have sufficient strength and at the same time they have to be flexible, elastic and easy to pleat and shape. Their simulation is not easy, as their behaviour is difficult to describe and predict. Nevertheless, computation algorithms have been developed over many years and evolved to such a level that today we are able to not only simulate simplified, static clothes, but also complex dynamically moving garments[1]. But, not only advanced computational models are responsible for precise virtual garment simulations. Also exact input parameters play an important role for a correct reproduction of the fabrics mechanical behaviour. For instance, newly-developed computation systems finally allow the simulation of the non-linear fabric behaviour; but in order to truly reflect these characteristics in the virtual computation, we have to be able first of all to measure them appropriately. Experimental values for the main mechanical and physical parameters can be derived from standard fabric characterization experiments such as the “Kawabata Evaluation System for fabrics” (KES) [2] and the “Fabric Assurance by simple Testing” (FAST) [3]. However, both characterisation methods have not been designed for the purpose of deriving parameters for virtual simulations thus special care must be taken when applying the obtained parameters to a dynamic simulation.

1.1. Mechanical properties of cloth

The mechanical behavior of fabric is inherent in the nature and molecular structure of the fiber material constituting the cloth, and as well the way these fibers are arranged in the fabric structure. Fabric fibers can be organized in several ways in the cloth surface.

Various types of fabrics are used in the textile industry. Woven fabrics can be arranged in different structures (Figure 1). They are relatively stiff though thin, easy to produce, and may be used in a variety of ways in many kind of design. In contrast, knitted fabrics are loose and very elastic. They are used for various purposes, including sports and leisurewear. This structure greatly influences the mechanical behavior of the fabric material, which is mainly determined by:

* The nature of the fiber: Wool, cotton, synthetic...
* The thread structure: Diameter, internal fiber and yarn structure...
* The thread arrangement: Woven or knitted, and particular pattern variation.
* The pattern properties: Tight or loose.

These properties are critical to the stiffness of the material, its ability to bend, and its visual appearance.

The mechanical properties of deformable surfaces can be grouped into four main families:

* Elasticity, which characterizes the internal forces resulting from a given geometrical deformation.
* **Viscosity**, which includes the internal forces resulting from a given deformation speed.

* **Plasticity**, which describes how the properties evolve according to the deformation history.

* **Resilience**, which defines the limits at which the structure will break.

![Figure 1: Different woven fabric patterns: Plain, Twill, Basket, Satin.](image)

Most important are the elastic properties that are the main contributor of mechanical effects in the usual contexts where cloth objects are used. Deformations are often small and slow enough to make the effect of viscosity, plasticity and resilience insignificant. One major hypothesis is that **quasistatic models** in the domain of elastic deformations will suffice for models intended to simulate the rest position of the garment on an immobile mannequin (draping). However, when a realistic animation is needed, the parameters relating energy dissipation through the evolution of the deformation are also needed, and complete **dynamic models** including viscosity and plasticity should be used.

Depending on the amplitude of the mechanical phenomena under study, the curves expressing mechanical properties exhibit shapes of varying complexity. If the amplitude is small enough, these shapes may be approximated by straight lines. This **linearity** hypothesis is a common way to simplify the characterization and modeling of mechanical phenomena.

It is common in elasticity theory to consider that the orientation of the material has no effect on its mechanical properties (**isotropy**). This however is inappropriate for cloth, as its properties depend considerably on their orientation relative to the fabric thread.

Elastic effects can be divided into several contributions:

* **Tensile elasticity**, deformations along the surface plane.

* **Bending elasticity**, deformations orthogonally to the surface plane.

Tensile elasticity is the most important and best studied aspect of fabric elasticity. It is usually described in terms of strain-stress relations. For linear elasticity, the main laws relating the strain $e$ to the stress $s$ involve three parameters, which are:

* **The Young modulus** $E$, summarizing the material's reaction along the deformation direction.

* **The Rigidity modulus** $G$, pertaining to oblique reactions.

* **The Poisson coefficient** $\nu$, characterizing the material's reaction orthogonal to the deformation direction, which is often neglected in the characterisation of fabrics.

While the described linear laws are valid for small deformations of the cloth, large deformations usually enter the nonlinear behavior of cloth, where there is no more proportionality between strain and stress. This is practically observed by observing a “limit” in the cloth deformation as the forces increases, often preceding rupture (resilience), or remnant deformations observed as the constraints are released (plasticity). A common way to deal with such nonlinear models is to assume weft and warp deformation modes as still being independent, and replace each linear parameter by nonlinear strain-stress behavior curves.

In order to create high fidelity dynamic simulations, these parameters must be obtained through measurements on real fabrics. This isn’t a simple task to perform because fabric is a very complex material, which has an isotropic behaviour. Thus special care must be taken when performing the measurements and applying them to a virtual simulation.

2. **Real World Fabrics**

2.1. **Measurement of fabric properties**

Each textile possesses typical characteristics, influenced by the textiles raw material (natural fibres, synthetics, etc.), yarn structures (degree of twist), planar structure (weave, knit) and finishing treatment, which are advantageous for some types of garments, but can be unfavourable for others, regarding garment comfort. Evaluating a fabric’s properties isn’t trivial thus various evaluation means were proposed. The simplest one, and still widely used
is the “fabric hand” concept. It consists of touching, squeezing and rubbing the fabric in one’s hand to evaluate its properties. This is a subjective measurement which cannot be used for the purpose of virtual simulations. Objective fabric characterization methods measure and relate the major mechanical properties, in order to obtain comparable information about textiles. The applied physical tests analyse and reflect the sensations felt during the subjective fabric assessment and describe them with a numerical value [4]. Important fabric properties are flexibility, compressibility, elasticity, resilience, density, surface contour (roughness, smoothness), surface friction and thermal attributes, which are the result of a broad fundamental research on fabric properties [5][6]. In virtual simulations, the main imitated mechanical properties are elasticity, shear, bending, density and friction. The KES system was developed in the 1970’s by Kawabata and constituted the first standardization of objective fabric assessments. Since, this method is widely used for the objective characterisation of fabrics, as well as for studies of fabric mechanical properties. In the late 1980’s the CSIRO Association in Australia realised the importance of a commercial measurement for wool fabrics and tried to offer a simpler and cheaper alternative to KES, the FAST method. Both, KES and FAST measure the same parameters; however different measurement principles are applied. The FAST method uses simpler procedures than KES and permits only a linear interpretation of the measured data, whereas KES provides a complete stress-strain profile for all measured characteristics. The measurements of both systems are conducted in the low force area, what corresponds to loads which a fabric is likely to undergo during garment manufacturing. Alternative, more flexible measurement devices exist for the measurement of tensile and hysteresis properties.

Elasticity tests are designed in a way to return the correlation between applied forces and corresponding fabric elongations. The FAST method measures the elasticity property at one load of 100 N/m along warp and weft direction. KES tests the tensile behaviour with an increasing force of up to 500 N/m also along weft and warp direction. After the tensile load attains the maximum force, the recovery process is recorded.

During shear tests, the required forces to change the angle between the orthogonal intersecting threads of textiles to certain extend are assessed. Whereas the tensile property is more influenced by the fabrics fibre composition and the yarn structure, the shear characteristic is mainly influenced by the fabric structure. Different measurement principles can be applied. The main standard method fixes the fabric between two clamps and applies opposite forces until a maximum angle (KES [2]) or maximum force is attaint. Other methods measure the fabrics extension-compression in the bias direction (FAST [3]) [7].

Regarding fabric bending tests, there are two main categories. The first category measures the bending deformation under the fabrics own weight. The most well known method within this category is the Cantilever test, which uses the engineering principles of beam theory. A fabric is moved forward to project as a cantilever from a horizontal platform. As soon as the leading edge of the fabric reaches an angle of 41.5° to the horizontal platform the bending length is measured (FAST). Another method of this category consists in the folded loop method, where the fabric is fold back on itself and the height of the loop measured. The second category of bending tests is designed to return the moment-curvature relationship by measuring forces or moments (KES). Therefore, a fabric is fixed between two clamps and bent in an arc of constant curvature, where the curvature changes continuously and applied moments recorded.

In contrast to elasticity, shear and bending, the friction property is not an internal but external mechanical force, varying with each other contact material. Distinctions are made between static and dynamic friction. The static friction is related to the initial force, what is needed to
overcome to start moving a material against another object or surface. The dynamic friction however occurs during the movement itself and is therefore generally lower than the initial static friction. There are several methods to assess friction. Within the standard fabric characterisation experiments (KES), the friction is measured by moving a piano-wire over the fabric at a constant force frequency. Friction is not measured by the FAST system.

2.2. Mapping to Computational Models

For the actual derivation of fabric input parameters, a mathematical description of the measured data is needed. Depending on the complexity of the implemented computational model and the available amount of measured data, this mathematical interpretation can be linear (from FAST) or non-linear (from KES and alternative devices).

The tensile behaviour of fabrics is strongly non-linear for most textiles. Strain-stress profiles of very elastic materials are particularly characterized by a curved envelope. Versatile computational models are able to simulate the nonlinear tensile behaviour and therefore ask for an adequate input data. Linear parameters derived from the measurement data from FAST, are correct in the low force area, occurring for example during static simulations, where the fabric is basically stressed by its own weight. However, linear parameters are incorrect for the simulation of higher stresses, as referring to them much lower loads are sufficient to achieve larger fabric elongations. Moreover, used in virtual garment fitting processes, linear parameters return a wrong feedback about the garment comfort (Figure 4).

![Figure 4: Simulation using KES tensile data (left) and FAST tensile data (right).](image)

At a first glance, the non-linear fabric parameters derived from the KES strain-stress envelopes seem to be better suited for the derivation of nonlinear tensile parameters. However the KES method is limited as well, as it returns the strain-stress profile only up to one maximum load. Dynamic cloth simulation is a much more complex issue. When the garment follows the movement of the mannequin, the fabric undergoes not only one but many deformations and relaxations of various low and high loads in different temporal distances. For that reason, derived parameters from KES are accurate for the one specific measured force (500 N/m), but not for various loads. Hence, for dynamic simulations, multiple load/unload experiments with different applied forces, which reflect what actually happens during the wear of a garment, are needed. Also, aspects which are related to the simulation history such as plasticity and properties which are time related such as viscosity, become important input characteristics for dynamic garment simulations. Until today, the viscosity of textiles is a little investigated field of research and no standard measurement exists for the characterisation.

Depending on the type of fabric material, the shear behaviour varies from linear to non-linear. State of the art simulation systems use a nonlinear shear computation model. Therefore, depending on the fabric material, a linear or nonlinear mathematical description is needed (Figure 5).

![Figure 5: Linear shear (top) and non-linear (bottom) shear strain-stress envelop.](image)

Similar to the tensile property, the nonlinearity of the shear behaviour can be more accurately derived from complete strain-stress envelopes, whereas the more linear shear comportment can be accurately interpreted from single measured forces as well. However, in contrast to the tensile property, the error in the comfort feedback for simplified nonlinear parameter is smaller. This is related to the fact that regarding shear, generally lower forces are concerned.
Even in versatile computation system, the complex bending property is still linear modelled. Thus, a simple (linear) mathematical interpretation for the bending behaviour is precise enough. The bending rigidity is returned by standard measurement methods as characteristic value. As this measure is a description of the slope between two major points of the measured data, it is suited to be directly taken as linear bending characteristic. The comparison of the bending rigidity obtained from the FAST and the KES measurement systems shows a good correlation for the bending rigidity value (Figure 6).

Figure 6: Virtual drape of a flannel piece of fabric.

2.3. Multi-Layered Fabrics and Seams

Regarding complete garments, not only the fabric characteristics are important for a mechanical accuracy and a good visual appearance. Additional clothing aspects, such as seams, interlinings and fabric fusing become important influencing factors for virtual computations and demand a separate examination.

Figure 7: Fitting and virtual simulation of a men suit.

2.3.1. Seams

Conventional garments are generally not composed out of only one, but many different pieces of fabrics. On the one hand, this is due to the complexity of the shape of the human body with its curves and bulges, which need to be covered by a fitted garment. On the other hand, this is related to changing tendencies and trends, which constantly ask for new silhouettes. Hence, as a garment is composed out of multiple single surfaces and they have to be somehow connected subsequently, in order to form a complete garment. The mechanical behaviour of a single textile and the behaviour of a tailored garment out of the same fabric are different as the characteristics of the junctions of the single surface pieces influence the general comportment as well. For the combination of two fabric pieces there several different methods:

The traditional way of combining two fabric pieces is by applying sewing techniques, where two or more surfaces are linked together with threads. Hereby, distinction can be made between different types of seams, such as the plain seams, the welt seams, the welding seams, decorative seams, etc. Their mechanical characteristics vary according the number of fabric layers and number of stitches and topstitches. The plain seam consists of two fabric layers, the outer fabric and the seam allowance (Figure 8) and is mainly used for standard fabric assemblies. The welt seam is composed out of three or more fabric layers, the outer fabric and two times or more the folded seam allowance, completed by one or two top-stitches (Figure 8). It is mainly used for parts of the garment, where a lot of abrasion is expected and also where additional stability is needed, as for example at the inner side of a pair of jeans. Modern high tech textiles, especially water proof garments are welded instead of sewed, as the stitches would impact their performance. Decorative seams are stitching in various patterns on top of the outer fabric. Whereas the decorative seams influence less the mechanical behaviour, the seams containing multiple fabric layers can change the fabric comportment significantly. Therefore, if we want to accurately imitate those parts of the garment, the seam mechanics need to be measured and accurately simulated as well. The stiffness of seams is an additional parameter, which can be specified inside the simulation application for each seam. Their characteristics can be obtained with the above described fabric measurement methods.

Figure 8: Plain seam (left) and welt seam with top-stitch (right).
Another important aspect regarding accurate seaming simulations is the problematic of seam pucker. Seam pucker is the occurrence of unwanted small fabric wrinkles at a garment’s seam, due to fabric gatherings caused by the sewing thread. Depending on the fabrics thickness and stiffness, this shrinkage can be up to 5% of the length of a seam. For an accurate virtual simulation, it is important to consider this parameter, as it influences the fit and especially the quality of the garment.

2.3.2. Multi-layered fabrics

In order to give to a garment more stability in some areas for functional or aesthetical reasons, a second fabric layers can be added. This second fabric layer is either permanently fixed to the outer fabric (fusing) or it is a loose additional textile (interlining). Regarding the permanently fixed fabric layer it is clear that the mechanical characteristics of the bonded combination of the two materials should be measured for their accurate virtual re-creation. However this can be easily accomplished by measuring not the single but the fused fabrics.

For the non-fixed fabric layers this is however a more difficult task. On the one hand the combination of both characteristics is needed, but on the other hand, the fabrics are single layers and for an accurate prototyping they should be treated separately. Simulating two layers of textile is very challenging. First, a stable and robust collision detection and response algorithm should be used in order to accurately model the interaction between the two layers. This is very difficult to do because most collision handling require a minimal distance – greater than the distance between 2 layers of fabric – to remain between the colliding objects. Second, a high number of polygons should be used, which would considerably slow down the simulation. Because of these two aspects it is suggested to also simulate the non-fixed fabric layers with only one virtual surface. Using mechanical characteristics which are a combination of materials, even the simulation of an endless amount of fabric-layers is possible with today’s simulation systems from a technical point of view.

Once the mechanical properties of a given fabric are obtained, they can be used to feed an animation system designed in such a way that the previously mentioned constraints are taken care of. This isn’t trivial either, and the design of such system is detailed in the next section.

3. Mechanical Models for Cloth Simulation

Cloth being approximated as a thin surface, its mechanical behavior is decomposed in in-plane deformations (the 2D deformations along the cloth surface plane) and bending deformation (the 3D surface curvature).

The in-plane behavior of cloth is described by relationships relating, for any cloth element, the stress to the strain (for elasticity) and its speed (for viscosity) according the laws of viscoelasticity. For cloth materials, strain and stress are described relatively to the weave directions weft and warp following three components: weft and warp and shear.

Assuming to deal with an orthotropic material (usually resulting from the symmetry of the cloth weave structure relatively to the weave directions), and null Poisson coefficient (a rough approximation), the weft, warp and shear components are independent, and the fabric elasticity is simply described by three independent elastic strain-stress curves.

In the same manner, viscoelastic strain-stress relationships relate the bending momentum to the surface curvature for weft, warp and shear. With the typical approximations used with cloth materials, the elastic laws are only two independent curves along weft and warp directions (shear is neglected).

The issue is now to define a model for representing these mechanical properties on geometrical surfaces representing the cloth. These curved surfaces are typically represented by polygonal meshes, being either triangular or quadrangular, and regular or irregular.

3.1. Continuum Mechanics

Continuum mechanics are one of the schemes used for accurate representation of the cloth mechanics. Mechanical equations are expressed along the curved surface, and then discretized for their numerical resolution. Such accurate schemes are however slow and not sufficiently versatile for handling large deformations and complex geometrical constraints (collisions) properly. Finite Element methods express the mechanical equations according to the deformation state the surface within well-defined elements (usually triangular or quadrangular). Their resolution also involves large computational charges. Another option is to construct a model based on the interaction of neighboring discrete points of the
Such particle systems allow the implementation of simple and versatile models adapted for efficient computation of highly deformable objects such as cloth.

### 3.2. Spring-Mass Models

The simplest particle system one can think of is spring-mass systems. In this scheme, the only interactions are forces exerted between neighboring particle couples, similarly as if they were attached by springs (described by an force/elongation law along its direction, which is actually a rigidity coefficient and a rest length in the case of linear springs). Spring-mass schemes are very popular methods, as they allow simple implementation and fast simulation of cloth objects. There has also been recent interest in this method as it allows quite a simple computation of the Jacobian of the spring forces, which is needed for implementing semi-implicit integration methods (see Section 4).

The simplest approach is to construct the springs along the edges of a triangular mesh describing the surface. This however leads to a very inaccurate model that cannot model accurately the anisotropic strain-stress behavior of the cloth material, and also not the bending. More accurate models are constructed on regular square particle grids describing the surface. While elongation stiffness is modeled by springs along the edges of the grid, shear stiffness is modeled by diagonal springs and bending stiffness is modeled by leapfrog spring along the edges. This model is still fairly inaccurate because of the unavoidable cross-dependencies between the various deformation modes relatively to the corresponding springs. It is also inappropriate for nonlinear elastic models and large deformations. More accurate variations of the model consider angular springs rather than straight springs for representing shear and bending stiffness, but the simplicity of the original spring-mass scheme is then lost.

### 3.3. Accurate Particle Systems

Because of the real need of representing accurately the anisotropic nonlinear mechanical behavior of cloth in garment prototyping applications, spring-mass models are inadequate, and we need to find out a scheme that really simulates the viscoelastic behavior of actual surfaces. For this, it is possible to use a particle system model that relates this accurately over any arbitrary cloth triangle through simultaneous interaction between the three particles which are the triangle vertices [1] [11]. Such a model integrates directly and accurately a strain-stress model using polynomial spline approximations of the strain-stress curves, and remains accurate for large deformations.

In this model, a triangle element of cloth is described by 3 2D parametric coordinates describing the location of its vertices on the weft-warp coordinate system. The precise weft, warp and shear strains of the surface may then be obtained through the positions of the triangle vertices using the Green-Lagrange tensor (Figure 10). Once the weft, warp and shear stresses are computed using the mechanical behavior of the material (typically, the strain-stress curves), the equivalent forces are then computed on the triangle vertices.

![Figure 10: A triangle of cloth element defined on the 2D cloth surface (left) is deformed in 3D space (right) and its deformation state is computed from the deformation of its weft-warp coordinate system.](image)

Such model offers, for not significantly higher computational requirements than spring-mass models, the accuracy of continuum-mechanics models, while still being formulated as a pure particle system (where particle forces are computed out of particle positions). This also allows the accurate reproduction of nonlinear strain-stress models which characterize cloth materials (Figure 11).
Figure 11: Drape accuracy between a simple spring-mass system along the edges of the triangle mesh (left) and the proposed accurate particle system model (center). Color scale shows deformation. The spring-mass model exhibits inaccurate local deformations, along with an excessive “Poisson” behaviour. This is not the case with the accurate model, which may still model the “Poisson” effect if needed (right, with a Poisson coefficient of 0.5). The spring-mass model is also unable to simulate anisotropic or nonlinear models accurately. The model can be extended to handle anisotropic curvature stiffness through bending momentums applied along edges, for which the angle between the adjacent elements give an evaluation of the local surface curvature along the orthogonal direction. Additional mechanical features are integrated in the model as well for simulating the behavior of complex garment features (Figure 12).

Figure 12: The proposed model simulates accurately anisotropic bending stiffness, with possible rest curvature defined on the surface (left). Rest curvature may also be defined along precise lines (center). Lines may also carry additional stiffness with their own custom rest length (right). All these features bring lot of potentialities for designing complex garment models.

4. Numerical Integration

The equations resulting from the mechanical formulation of particle systems do usually express particle forces depending on the state of the system (particle positions and velocities). In turn, particle accelerations is related to particle forces and masses by Newton's 2nd law of dynamics. This leads to a second-order ordinary differential equation system, which is turned to first-order by concatenation of particle position and velocity. A vast range of numerical methods has been studied for solving this kind of equations.

4.1. Discussing Integration Methods

4.1.1. Implicit Integration Methods

The most widely-used method for cloth simulation is currently the semi-implicit Backward Euler method, which was first used by Baraff et al [8] in the context of cloth simulation. As any implicit method, it alleviates the need of high accuracy for the simulation of stiff differential equations, offering convergence for large timesteps rather than numerical instability (a step of the semi-implicit Euler method with "infinite" timestep is actually equivalent to an iteration of the Newton resolution method) [12].

Better accuracy can be obtained through the use of the 2nd-order Backward Differential Formula (BDF-2), as described by Hauth et al [10]. This uses the previous state of the system for enhancing accuracy up to 2nd-order, with a minimal impact on the computation charge.

Compared to Backward Euler, the main interest of the BDF-2 method is that it exhibits better accuracy for dynamic simulation over time (less numerical damping) for moderately stiff numerical contexts (at the expense of reduced robustness for nonlinear situations). For very stiff contexts however, this benefit disappears. While it is possible to implement higher-order BDF methods, their interest is reduced by their lack of stability, and high accuracy could be more efficiently reached using high-order explicit methods. Stability of implicit methods is also affected by the nonlinearities of the mechanical model.

Figure 13: Stability test: A square of cloth is initially deformed with large random perturbations, and then simulated using various timesteps.
4.1.2. Explicit Integration Methods

Unlike implicit methods, explicit methods do not offer convergence to equilibrium if the timestep is too large compared to the numerical stiffness of the equations. On the other hand, they are very simple to implement, and compute much faster than their implicit counterpart for reaching a given accuracy. This is particularly true for high-order methods, which offer very high accuracy if the timestep is small enough, but diverge abruptly if it exceeds a threshold (related to the stiffness of the equations). This is why an efficient timestep control scheme is essential for the implementation of these methods.

While the explicit 1st-order Euler and 2nd-order Midpoint methods should be restricted to simple applications (beside their simplicity, they have no benefits compared to their implicit counterparts), a popular choice is the 5th-order Runge-Kutta scheme with embedded error evaluation [13]. It is a six-stage iteration process where the computed error magnitude can be used for controlling the adequate timestep very accurately, depending on accuracy and stability requirements. Unlike implicit methods, this method yields a very good guaranteed accuracy (resulting from the high-order, but which may require very small timesteps), which is particularly important for problems where energy conservation is a key issue (for example, evaluating the effect of viscous parameters in the motion of fabrics) (Figure 13). On the other hand, explicit methods are quite unsuited for the fast relaxation of the static cloth draping applications.

Figure 14: Evaluation of numerical damping of various integration methods using energy dissipation plots along time (50cm x 50cm square cloth, initially horizontal, attached along one edge, linear isotropic 100N/m, 100g/m2, 2cm² elements, no dissipative parameters). 5th-order Runge-Kutta (up) accurately preserves the total energy along time, a good amount of it being transferred to elastic energy through small-scale mesh jittering (timesteps between 0.0001s and 0.00001s). Implicit methods such as Inverse Euler (down) damp small-scale motion.

4.2. Implementation Issues

While there are no particular issues related to the implementation of explicit integration methods, semi-implicit methods require the resolution of large sparse linear equations systems, which are mainly constructed from the Jacobian of the mechanical law (their sparse structure relates the mechanical dependency between the particles). Among possible speed-up approximations, the Implicit-Explicit method described in [14] neglects the Jacobian terms generated by the non-stiff forces (which are then explicitly integrated).

A choice candidate for resolving this linear system is the Conjugate Gradient method, which is iterative and thus offers compromise between computation charge and symmetric accuracy, and which also allows efficient implementation for sparse systems.
Among possible optimizations are linearization schemes aimed at performing the computation using a constant approximation of the Jacobian, so as to implement preprocessing optimizations in the resolution. While giving reasonable benefits for draping applications, these approximations however generate large "numerical damping" that slow down convergence and alter highly the motion of the cloth along time [15] [16] [17] [18].

The only solution for simulating the accurate motion of cloth was indeed to use real value of the Jacobian corresponding to the current state of the system. We have taken advantage of the Conjugate Gradient method which only needs the Jacobian matrix products with given vectors to compute these products "on the fly" directly from the system state, skipping the sparse explicit storage of the matrix for each frame. Our system actually allows performing partial linearization of the Jacobian, so as to use the linearization ratio offering the best tradeoff between motion accuracy and stability, depending on the simulation context.

5. Collision Processing

Collision detection is indeed one of the most time-consuming tasks when it comes to simulate virtual characters wearing complete garments [19]. This task is performed through an adapted bounding-volume hierarchy algorithm, which uses a constant Discrete-Orientation-Polytope hierarchy constructed on the mesh, and optimization for self-collision detection using curvature evaluation on the surface hierarchy. This algorithm is fast enough for allowing full collision and self-collision detection between all objects of the scene with acceptable impact on the processing time (rarely exceeds 20% of the total time). Thus, body and cloth meshes are handled totally symmetrically by the collision detection process, ensuring perfect versatility of the collision handling between the body and the several layers of garments [20].

Collision response is handled using a geometrical scheme based on correction of mesh position, speed and acceleration. This scheme ensures good accuracy and stability without the need of large nonlinear forces that alter the numerical resolution of the mechanical model. Our model simulates contact forces through a perfectly damped reaction model, associated to a Coulombian (solid) friction model.

The implemented collision model ensures full mesh-to-mesh collision response, which can deal with very complex multilayer collisions configurations involving several surfaces. The collision processing is therefore general enough for handling contacts between the several garments of a complex dress style, as well as the interactions between complex fold patterns when animating ample gestures. The model is also accurate enough for reproducing accurately friction behavior, allowing for example pants to hold to the waist with friction alone during character motion, without "cheating" using geometrical attachments. Good stability allows the simulation of complete multilayer garments with millimeter collision thickness despite large cloth speed and tension produced by complex character motion.

6. Case Study

6.1. High Fashion in Equation

Tailored out of exquisite materials and artful designed patterns, high fashion garments constitute the most sophisticated kind of clothes. The unique manufactured pieces, only affordable for a small circle of clientele, are not only envelopes for the human body, but artworks, visualizing cultural aspects, tendencies and trends. Historical haute couture garments are characterized by an additional aspect: Time specific garment details, which allow their affiliation to certain époques, become visible.

The computation of this kind of art pieces can thus be seen as the most challenging part in the field of virtual garment simulations, an area that was not touched on before. It represents new challenges for the computation system as well as for the realization of the design. With the 3D animation “High Fashion in Equations” MIRALab-
University of Geneva brought to life virtually 18 Haute Couture garments from the 1950’s to the 1960’s after designs from Marc Bohan, Serge Guérin and Hubert de Givenchy, former assistants of the Swiss couturier Robert Piguet.

6.2. Design and implementation

The overall visual appearance of a garment (real or virtual) is influenced by two main components: The shape of the 3D garment, determined by the corresponding 2D pattern and the fabric material used which behavior is influenced by its mechanical and physical properties.

6.2.1. 2D Patterns

The creation of high fashion 2D patterns is a precise handiwork. Having the desired 3D shape in mind, a flat pattern is drawn by skilled experts according to pattern construction rules. Therefore, ancient garments of that period have been studied for a better comprehension of former pattern making methods [21]. The look of the garment silhouettes of the 1950’s and 1960’s is also influenced by the beauty ideal of that time. The post war period is characterized by the typical wasp waist.

The virtual garments have been composed with Miralab’s virtual garment creation software, which imitates the real world tailoring process: the patterns are initially designed and cut in 2D space, placed around a virtual mannequin in 3D space, sewn together to make a completed clothing. New innovative design tools allow the fast alteration of the elaborated 2D patterns both in 2D and 3D with real-time preview of the 3D garment. During fitting, the system automatically evaluates the comfort of the garment on the overstated body with its wasp waist silhouette. Based on the mechanical interactions between the cloth and the body, the designer receives the feedback for optimizing the pattern shape. Other important features, inevitable for those challenging calculations, are a powerful collision response method able to simulate multilayer cloth with stability and robustness, complemented with an intersection recovery system for addressing the possible remaining problematic situations [22].

6.2.2. Fabric materials

Since only precisely computed fabric characteristics can visualize the exquisite fabric qualities of high fashion garments, their correct derivation from real fabric characteristics plays an important role. Information on the fabrics used for those designs was limited to material descriptions regarding structure and fiber compositions. Therefore, similar fabric materials have been chosen and measured with fabric characterization experiments, to obtain strain-stress curves for the main mechanical and physical fabric properties, which were fitted with polynomial splines.

Finally, the garments are simulated using the accurately derived physical and mechanical fabric properties. During the animation, the garment follows the movement of the virtual mannequin. The movements of the mannequins have been inspired by poses of ancient drawings of that period.

7. Conclusion

Interactive design can already be used for creating fashion models that have enough realism for reproducing accurately the behavior of real garments. Thanks to inputs measured from real fabrics along with good time-accurate numerical techniques, our system is able to compute realistic animations of complex garments.

The core technologies of this system are now being adapted to actual needs of the garment industry through collaborative projects, which deal on mechanical characterization of fabrics, virtual prototyping, manufacturing processes, e-commerce. Although some advances are still welcome in the area of efficiency and accuracy of mechanical simulation techniques, the challenge is now to create new tools that will ensure to the garment industry a smooth transition from
tradition to novel possibilities offered by virtual simulation.

Figure 18: Efficient and robust collision processing is important for simulating complex cloth.

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