

3D Virtual Clothing: from Garment Design to Web3D Visualization and Simulation

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ABSTRACT

One of the major challenges in Computer Graphics concerns the 3D representation and physically-based simulation of garments. In our research, we are working closely with the textile industry, investigating three different classes of problems. First, we aim at developing techniques and methods for cloth simulation specifically aimed at the Web3D context. Second, we are defining a cross-application data exchange format among the different CAD systems and applications used in the textile industry, including the additional information needed to support 3D simulations. Third, we are implementing a tool that complements traditional textile CAD systems (which are based on 2D graphics), allowing the user to automatically obtain VRML-based 3D previews of the garment (for evaluating garment designs and also easily publishing them on the Web). This paper illustrates the results we have achieved in these three directions.

Categories and Subject Descriptors

I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling – *Physically based modeling*. I.3.6 [Computer Graphics]: Methodology and Techniques – *Interaction techniques and standards*. I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism – *Animation, and virtual reality*. H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems – *Artificial, augmented, and virtual realities*. J.6 [Computer-Aided Engineering]: *Computer-aided design (CAD)*.

General Terms

Algorithms, Performance, Design, Standardization.

Keywords

Physically-based simulation, virtual clothing, cross-application data exchange format for the textile industry, CAD tools for garment design, Product Visualization, VRML/Java, XML.

1. INTRODUCTION

Physically-based computer animation is one of the relevant research areas in Computer Graphics [17]. One of the several challenges in this area concerns the 3D representation and simulation of garments. This is crucial for industries as different as the movie industry (that needs to include very realistic animated characters in its productions) and the fashion and textile industry, whose purpose is twofold: on one side, they would like to build virtual prototypes of garments for evaluating a design without the need for actually producing it; on the other side, they would like to develop virtual try-on applications allowing consumers to see how a garment fits on their individual body measures.

An ideal 3D garment simulation should be both very efficient (e.g., real-time animation) and high-fidelity (e.g., deformations of cloth caused by the shape of a specific human body, different behaviors determined by the materials of which the garment is made). Unfortunately, the high computational complexity of the simulation makes it very difficult to achieve both goals: existing systems are tailored to favor one of the two. Systems that are capable of real-time animation can produce impressive results, but are of scarce interest to the textile industry, because the obtained results are not reliable and cannot be used to predict how the actual garment will look and behave in the physical world. High-fidelity simulation of a garment might require hours of computation to produce a few seconds of animation. However, while its results are highly realistic and satisfactory from the point of view of the movie industry, it still presents open issues (e.g., integration with existing textile design tools) from the point of view of the fashion designer. In our research, we are working closely with the textile industry (in particular, with the Benetton Group), investigating three different classes of problems.

First, we are developing techniques for cloth simulation aimed at building a garment simulation engine for the Web3D context.

Second, we are defining a cross-application data exchange format aimed at allowing data interchange among the different CAD systems and applications used in the textile industry, including the additional information needed to support 3D simulations.

Third, we are implementing a tool that complements traditional textile CAD systems (which are based on 2D graphics), allowing the user to automatically obtain VRML-based 3D previews of the garment (for evaluating garment designs and also easily publishing them on the Web). The tool is based on the previously mentioned simulation engine and interchange format.

This paper illustrates the results we have achieved in the three directions.

2. THE TEXTILE INDUSTRY CONTEXT

In this section, we briefly illustrate the typical design and production chain followed in the textile industry, to better motivate the need for 3D virtual prototyping systems.

Garment production starts from garment conception and design. For many new concepts of garment, tailors must be involved in the design process to produce actual prototypes for evaluation and market research purposes. Results of market research can lead to discarding the design or changing it (in the latter case, another prototype needs to be produced and evaluated). This is a very expensive iterative process for the industry: for any accepted design, many more are discarded and will not go into production.

Since the production process is based on cutting and stitching together parts of cloth, traditional textile CAD systems are aimed at drawing these 2D parts and driving automatic cutting procedures (e.g., Gerber Technology [11], Investronica Sistemas [13]). Procedures for stitching parts (and accessories such as buttons, zips,...) are not handled by the CAD system and require human operators to program the stitching machines.

To improve the efficiency of the garment conception and design phase, a proposed solution is to adopt virtual prototyping techniques. Exploiting 3D virtual garment models would allow the industry to dramatically reduce both the time before going to market and the work costs. Moreover, virtual prototypes can be reused for an additional purpose, i.e. 3D product visualization on the Web.

It must be noted that 3D virtual prototyping requires to extend existing CAD systems (or propose tools that complement them) to handle additional information (e.g., stitching data) needed to define the 3D model and to provide high fidelity simulation of the garment. Unfortunately, no solutions have been yet proposed for these problems in the textile industry.

In our research, we are pursuing both goals to propose an integrated system. In particular, we aim at defining a flexible simulation engine that allows the user to choose the desired tradeoff between performance and fidelity. For example, given a short computation time, one could choose between an high *fidelity* garment simulation in a *static* mannequin positions or an high *performance* garment simulation on *animated* mannequins.

3. A QUICK INTRODUCTION TO GARMENT SIMULATION

Garment simulation and visualization is a complex task that can be subdivided in four main subtasks:

- Geometrical definition of garment parts and of objects that will interact with the garment (e.g. a specific human body);
- Optical laws simulation (rendering);
- Dynamic laws simulation (forces, accelerations, velocities, energies);
- Interaction with the environment (collision detection and response). Garment simulation is mainly concentrated on the interaction between the different parts of the garment and the virtual body (mannequin).

While, the first two issues are classic 3D graphics problems, the last two require to face the following problems:

- *Cloth behaviour simulation*: cloth simulation concerns the mechanical model adopted for garment parts behaviour approximation. It can be a parametric model to allow different material simulation (e.g., cotton, wool, silk,...).

- *Handling of constrictions*: constrictions concern limitations of garment movement such as those caused by the seams between parts of a garment or by placing the garment on a coat hanger.
- *Collision detection*: Collisions must be detected between the garment and the human body as well as garment parts themselves (self-collisions).
- *Physically-based response*: Every collision needs a response to avoid interpenetration and simulate friction and bouncing effects.

Initial work on the simulation of garments [10] concentrated only on the geometrical features of deforming cloth, while the first physically-based models were proposed in the early '90s [6] [20]. Different physically-based approaches have been proposed, e.g. some exploit particles systems for mechanical simulation [5][8] while others employ continuous models resolved by finite elements [9]. Although finite elements have shown the greatest accuracy (at high computational costs), particles systems became the preferred approach in the computer graphics community for their simplicity, flexibility and their fidelity/performance ratio.

In general, computational costs are mainly due to numerical integration of the ODE (Ordinary Differential Equation) systems that model the cloth, and to collision detection needs. From the point of view of numerical integration, existing approaches might use either *explicit* or *implicit* methods. Classic explicit integration methods such as Euler, Midpoint, or Runge-Kutta are relatively easy to implement, but need very small integration steps to guarantee system stability. Implicit methods (e.g., the implicit versions of the three classic methods mentioned above) are able to use larger steps without loss of stability, but are more complex to implement because they need to solve large linear systems at every integration step. The use of implicit methods in cloth simulation was first proposed by [2].

From the point of view of collision detection, heuristics are typically used to limit the number of collision tests to be performed. In particular, the most used heuristics are space subdivision (e.g., voxel, octree, bounding-box) and hierarchical orders. A specific problem of cloth simulation is the need of managing self-collisions. To this purpose, good results have been achieved in [21] where the global surface is partitioned in smaller parts whose dimension is inversely proportional to the curvature of the parts themselves. This subdivision allows one to avoid performing self-collision tests on those parts that do not reach the needed curvature.

4. A JAVA/VRML CLOTH SIMULATOR

As we have previously seen, garment simulation is a complex task both from a conceptual and computational point of view. Research in this field often exploits very fast and expensive graphics workstations and proprietary environments. In our work, we are interested in exploiting conventional hardware and platform-independent software to be used also on the Web.

In this Section, we propose a cloth simulation engine based on VRML and Java. First, we illustrate the modelling and algorithmic choices we made; then, we discuss how they were implemented in VRML/Java.

4.1 Simulation method

One of the main tradeoffs in cloth simulation is the one between fidelity and performance. Considering the intended context of use for our simulator, we offer some variable settings by which the

user can choose to trade some performance in favor of more fidelity or vice versa. A generic physically-based simulator runs in a loop, containing the following four main activities [17]:

- **Force computation:** there are a lot of forces to be managing for reproduce real world phenomena. Gravity for example is a most important one, but other forces such as air viscosity and wind improve the simulation fidelity. More kinds of force we consider, more results are similar to real world ones.
- **Collision detection:** graphical objects are defined geometrically and located in a 3D virtual environment; when two objects reach a contact point (or a interpenetration) the collision detection algorithm musts to recognise it and notify the details to collision response task.
- **Collision response:** the collision between two objects produces forces that modify positions and velocities according with conservation laws when collision is elastic, otherwise with energy dispersion.
- **State integration:** simulator works by discrete time steps. When forces are computed these produces acceleration on objects. During time step this acceleration is considered constant and so we can use cinematic laws or advanced integration techniques for compute new object positions.

For animation purposes, we need to know particles position at close time instants (e.g., the temporal distance between one position and the following one should be 33ms to obtain a 30fps animation). However, stable state integration often requires smaller integration steps.

4.1.1 The Adopted Mechanical model and Super-elasticity Issues

For cloth modeling purposes, we adopt a particle system approach based on a mass-spring model. In the literature, the mass-spring model is widely used to simulate any elastic body. A typical good topology for a mass-spring model aimed at cloth simulation is illustrated in Figure 1. The nodes represent mass elements, the arcs between nodes represent spring elements, and the modeler can define several parameters such as particle mass value; elastic constants for traction (in weft and warp direction), bending (in weft and warp direction), shearing; constants for damping, friction and bouncing.

By using different settings for the parameters, it is possible to simulate different kinds of cloth. For example, Figure 6 shows the simulation of two different cloths (the right one is lighter and more elastic than the left one).

A well known problem of mass-spring models is the super-elasticity effect, i.e. small elastic constant produce unrealistic cloth behaviour (due to excessive spring extension). A simple way to minimize this undesired effect is to decrease elasticity settings, but, as a result, the ODE system that models the mass-spring topology can become stiff, and lead to instability.

There are both numerical and empirical solutions to the super-elasticity problem. Numerical solutions are based on implicit integration, but its implementation is complex as already mentioned in Section 3. Empirical solutions for explicit methods have been proposed by [16] [19] and are based on limiting the extension of the spring. More specifically, Provot [16] manipulates directly the position of particles when the extension becomes excessive, and then applies an inverse dynamics procedure for the global distribution of modifications (this procedure ends up adding computation time). The approach by Vassilev [19] temporarily sets to zero the extension velocity of

those particles that are showing super-elasticity effects to prevent further extensions (note that, in explicit integration methods, the position of a particle at time $t+1$ is given by its position at time t plus its velocity multiplied by the integration step). Unfortunately, this solution produces discontinuous (unrealistic) behaviours.

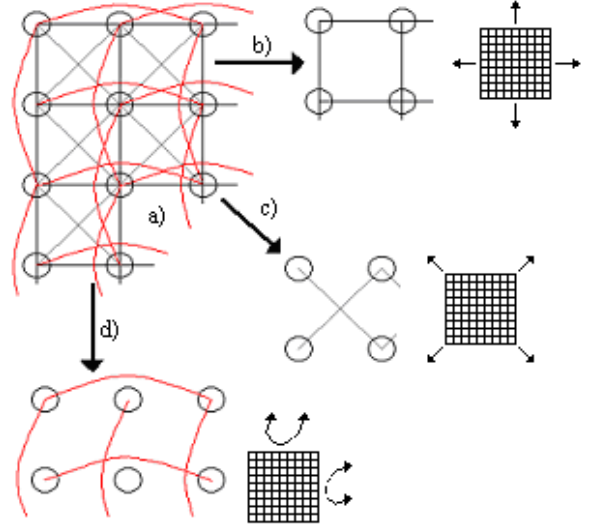


Figure 1. Mass-spring topology: a) global structure; b) vertical and horizontal springs; c) shearing springs; d) bending springs.

However, the super-elasticity effect tends to affect meshes whose resolution (i.e., the number of mass and spring elements for unitary area) is high. Therefore, our system adopts the following approach. If the user requires a fast simulation by setting a low resolution for the mesh, we do not take actions to prevent super-elasticity effects (because they are minimal), and we instead concentrate on reducing anti-aesthetic effects (due to the large area of polygons in a low-resolution mesh). To do so in a simple and efficient way, we increase the “creaseAngle” parameter of IndexedFaceSet. This setting allows one to control when the smoothing of edges performed by the VRML rendering engine should be performed. The `creaseAngle` is a threshold: if the angle between two edges is less than `creaseAngle`, then the smoothing is performed, otherwise the faces will appear faceted (see Figure 2).



Figure 2. The same geometric model with a low value (left), and an high value (right) of `creaseAngle`.

If the user trades efficiency in favor of more fidelity by increasing the resolution of the mesh, the system offers the possibility of increasing rigidity settings (to minimize super-elasticity effects) and decreasing the size of the integration step (to prevent instability).

4.1.2 Forces

Time evolution of particle system is determined by resultant forces exerted on each particle. Some forces originate from internal factors in the mechanical model of the cloth, other are due to external environmental factors such as gravity, viscosity, wind, constriction and collision. We consider all these contributions and compute the resulting force for each particle by using the following equations:

$$\mathbf{f}_g = m\mathbf{g}$$

$$\mathbf{f}_v = -k_v \mathbf{v}$$

$$\mathbf{f}_e = -\left[k_e (|\mathbf{l}| - r) + k_d \frac{\mathbf{l}' \cdot \mathbf{l}}{|\mathbf{l}|} \right] \frac{\mathbf{l}}{|\mathbf{l}|}$$

where m is the particle mass, \mathbf{g} the gravitational constant, \mathbf{f}_g the gravitational force, \mathbf{v} is the particle velocity, k_v is the fluid (e.g., air, water) viscosity constant, \mathbf{f}_v is the viscosity force, \mathbf{l} is the spring length (between two particles), \mathbf{l}' is the elongation velocity, r is the rest position of the spring, k_e is the elastic constant of the spring (Young module), k_d the damping constant of the spring, \mathbf{f}_e is the elastic force exerted on the particle linked to the spring ($-\mathbf{f}_e$ in the case of the particle linked to the other side).

Wind forces are proportional to scalar product between wind direction and the normal of each face of the cloth.

4.1.3 Collision detection and response

The algorithms we currently use compute collisions by using geometric data from IndexedFaceSet VRML nodes. Geometrical detection of collisions is simply performed from each particle of the cloth and each face of the colliding object. We are working to improve this naive method using space subdivision techniques. Collision response modifies forces and velocities as described in [15]. This technique allows us to control friction and bouncing effects.

4.1.4 Numerical integration

Given the resulting force that acts on a particle we can compute its new position in 3D space using Newton's first law and classic cinematic laws.

More specifically, from equation $\mathbf{f} = m\mathbf{a}$ (where \mathbf{f} is the resultant force vector acting on the particle, and m its mass value), we obtain \mathbf{a} (the acceleration vector).

Considering the one-dimensional case, continuous cinematic law at constant acceleration $x = d^2a/dt^2$ determines the position of the particle at time t . Introducing velocity, one obtains two differential equations: $v = da/dt$ and $x = dv/dt$. The state of a particle at time t is completely determined by position and velocity values. In the 3D case, we represent this by the vector $[x_1 \ x_2 \ x_3 \ v_1 \ v_2 \ v_3]$, a generic element of a six-dimensional phase space. This notation allow us to write the differential operator as follows:

$$\mathbf{x}' = [x_1' \ x_2' \ x_3' \ v_1' \ v_2' \ v_3'] = [v_1 \ v_2 \ v_3 \ f_1/m \ f_2/m \ f_3/m]$$

Suppose that force $\mathbf{f} = [f_1 \ f_2 \ f_3]$ depends only on \mathbf{x} and t , we can write the ODE:

$$\mathbf{x}' = F(\mathbf{x}, t)$$

Starting from an initial value $\mathbf{x}_0 = \mathbf{x}(t_0)$, we can solve the ODE with several integration methods. Our simulation engine implements three explicit methods: Euler, Midpoint, and fourth-order Runge-Kutta.

The simplest method (Euler) produces an approximation value as follows:

$$\mathbf{x}(t_0 + h) = \mathbf{x}_0 + h\mathbf{x}'(t_0)$$

where h is the integration step.

This method is formally justified by *Taylor's series*:

$$\mathbf{x}(t_0 + h) = \mathbf{x}_0 + h\mathbf{x}'(t_0) + (h^2/2!)\mathbf{x}''(t_0) + (h^3/3!)\mathbf{x}'''(t_0) + \dots + (h^n/n!)(\partial^n \mathbf{x} / \partial t^n) + \dots$$

where one can easily notice that the Euler method is based on deleting the parts of the series that contain higher order derivatives. Accuracy of approximation is determined by the temporal extent of the integration step and the size of the values of the higher order derivatives that have been ignored by the method.

Midpoint methods uses instead the following equation:

$$\mathbf{x}(t_0 + h) = \mathbf{x}_0 + h(f(\mathbf{x}_0 + (h/2)f(\mathbf{x}_0)))$$

Finally, these are the equations of fourth-order Runge-Kutta:

$$k_1 = hf(\mathbf{x}_0, t_0)$$

$$k_2 = hf(\mathbf{x}_0 + k_1/2, t_0 + h/2)$$

$$k_3 = hf(\mathbf{x}_0 + k_2/2, t_0 + h/2)$$

$$k_4 = hf(\mathbf{x}_0 + k_3, t_0 + h)$$

$$\mathbf{x}(t_0 + h) = \mathbf{x}_0 + (1/6)k_1 + (1/3)k_2 + (1/3)k_3 + (1/6)k_4$$

For the mathematical justification of these methods, we refer the reader to numerical analysis textbooks (e.g. [3][7]).

The use of implicit methods has not been considered to avoid increasing the complexity of the simulator.

4.2 Simulating cloth parts and garments

The simulation method described in the previous section has been implemented with a Java class. We now introduce the three main VRML nodes (*SimulationScript*, *Garment* and *ObjectCollider* PROTOs) that allow one to invoke the simulation method inside the 3D world. The physics simulation obtainable with these nodes considers gravity, viscosity, wind and collision detection between a textile part and a user-defined object (it will be typically a mannequin, but it can also be any other object, e.g., a chair or table). The structure of the *SimulationScript* node is the following:

```

1 DEF SimulationScript Script
2 {
3   mustEvaluate TRUE
4   eventIn SFTime DefineClothGeometry
5   eventIn SFTime ComputeNewFrame
6
7   field SFNode garment USE UserDefinedGarment
8   field SFNode collider USE UserDefinedObject
9
10  field SFFloat viscosity_const 0.2

```

```

11 field SFFloat x_wind_intensity 10.0
12 field SFFloat y_wind_intensity 10.0
13 field SFFloat z_wind_intensity -100.0
14 field SFFloat wind_turbulence 10.0
15 field SFFloat integration_step 0.0025
16 field SFInt32 ODESolverType 0
17 field SFInt32 iterations
18 eventOut MFVec3f coord
19 eventOut MFInt32 coordIndex
20 eventOut MFVec2f texturecoord
21 eventOut MFInt32 texturecoordIndex
22 eventOut MFVec3f collisioncoord
23 eventOut MFInt32 collisioncoordIndex
24
25 url "Simulator.class"
26 }

```

This node is responsible to communicate all the needed parameters to the simulation engine, that is encapsulated in the Java class “Simulator.class” (line 25). At line 3, the `mustEvaluate` flag tells the player that it cannot ignore the script execution. At line 4 and 5, two `eventIn` are respectively used to initialize (DefineClothGeometry) the simulator and require the production of new animation frames (ComputeNewFrame). At line 7 and 8, one can specify a garment (garment field) and an object that might collide with it (collider field). At line 10, viscosity determines the resistance of the fluid (typically air) into which cloth is immersed. Line 11 through 14 contain wind parameters (direction and turbulence). At line 15, 16 and 17, one can respectively specify the integration step, choose the integration method (Euler, Midpoint, Runge-Kutta) and set the number of iterations that the integration method has to perform for each generated frame. Lines 18 through 23 contain `eventOut` events: `coord` and `coordIndex` control the garment geometry, `texturecoord` and `texturecoordIndex` control the texture mapping on the garment, the last two events allow the simulator to control the geometry of the possibly colliding object.

The Garment PROTO is defined as follow:

```

1 PROTO Garment
2 [
3   exposedField MFVec3f coordinate []
4   exposedField MFInt32 index []
5   exposedField SFVec3f size 1 1 1
6   exposedField SFRotation rotation 0 0 1 0
7   exposedField SFVec3f translation 0 0 0
8
9   exposedField SFInt32 weft_particles_num 50
10  exposedField SFInt32 warp_particles_num 50
11  exposedField SFFloat particle_mass 0.1
12  exposedField SFFloat weft_elastic_const 1800
13  exposedField SFFloat warp_elastic_const 1800
14  exposedfield SFFloat
15    weft_bending_elastic_const 400
16  exposedfield SFFloat
17    warp_bending_elastic_const 400
18  exposedfield SFFloat
19    shear_elastic_const 400
20  exposedfield SFFloat
21    elastic_damping_const 0.1
22  exposedfield SFFloat
23    objectcloth_friction_const .5
24  exposedfield SFFloat
25    objectcloth_damping_const .3
26 ]
27 {
28   eventIn MFVec3f coordIN
29   eventIn MFInt32 indexIN
30   eventIn MFVec2f texturecoordIN
31   eventIn MFInt32 textureindexIN
32 }

```

```

27 Shape
28 {
29   geometry DEF GarmentShape IndexedFaceSet
30   {
31     coord DEF GarmentCoord Coordinate 32
32     { point IS coordinate }
33     coordIndex []
34     solid FALSE
35     creaseAngle 3.1
36     texCoord DEF TextureCoord
37     TextureCoordinate { point [] }
38     texCoordIndex []
39   }
40   appearance Appearance {...}
41 }
42 DEF EventLinkScript Script {...}

```

GarmentShape (line 29) is an `IndexedFaceSet` that defines the initial garment geometry (automatically generated with the tool we describe in Section 5.2). Every vertex of the *GarmentShape* corresponds to a particle. The change of the particle position computed by the simulator class produces the change of the *GarmentShape* geometry. Parameters at line 9 and 10 allow one to choose the number of particles in the mesh, while line 11 defines the particle mass. Line 12 through 17 contain the parameters for the springs. They control respectively elastic extension in weft and warp direction, elastic bending in weft and warp direction, elastic shearing and the damping constant for all these spring types. Lines 18 and 19 specify the object-cloth collision parameters: the friction and the damping constants respectively determine the sliding and bouncing behaviors of the particles over the object. `EventLinkScript` (line 41) is needed to link the `eventIn` events of the PROTO to the *GarmentShape* elements (e.g., the event `coordIN` is linked to *GarmentShape* coordinates).

The `UserDefinedObject` (line 8 of *SimulatorScript*) is an instance of the `ObjectCollider` PROTO:

```

PROTO ObjectCollider
[
  exposedField MFVec3f coordinate []
  exposedField MFInt32 index []
  exposedField SFVec3f size 1 1 1
  exposedField SFRotation rotation 0 0 1 0
  exposedField SFVec3f translation 0 0 0

  eventIn MFVec3f coordIN
  eventIn MFInt32 indexIN
]

```

Its structure is very simple and allows one to define an `IndexedFaceSet` using `coordinate` and `index` `exposedFields`.

The following is the event sequence that controls a simulation (*Agarment* is an instance of the Garment PROTO and *Acollider* is an instance of the `ObjectCollider` PROTO):

```

1 ROUTE Touch.touchTime
2   TO SimulationScript.DefineClothGeometry
3 ROUTE Touch.touchTime
4   TO Timer.startTime
5 ROUTE Timer.cycleTime
6   TO SimulationScript.ComputeNewFrame
7 ROUTE SimulationScript.coord
8   TO Agarment.coordIN
9 ROUTE SimulationScript.coordIndex
10  TO Agarment.indexIN
11 ROUTE SimulationScript.texturecoord
12  TO Agarment.texturecoordIN

```

```

13 ROUTE SimulationScript.texturecoordIndex
14     TO Agarment.textureindexIN
15 ROUTE SimulationScript.collisioncoord
16     TO Acollider.coordIN
17 ROUTE SimulationScript.collisioncoordIndex
18     TO Acollider.indexIN

```

The TouchSensor called *Touch* (line 1) is used to start the simulation: its eventOut is routed into *SimulationScript* to initialize the simulation. *SimulationScript* accepts the event and builds both the particle system and the coordinates of the *GarmentShape*. The same TouchSensor starts a TimerSensor called *Timer* (lines 3-4), that sends to *SimulationScript* (lines 5-6) a cycleTime event every 25ms. As a response, *SimulationScript* computes a new frame, returning the new coordinates and texture mapping for *GarmentShape* (lines 7-14), and the coordinates for the possible colliding object (lines 15-18).

The Java class responds to the ComputeNewFrame eventIn with the following code:

```

1  if(event_name.equals("ComputeNewFrame"))
2  {
3      int it;
4
5      for(it=0; it<iterations; it++)
6          Integration();
7
8      // EventOut:
9      coord_obj.setValue(position);
10 }

```

that performs a number of numeric integration steps equal to those specified by the iteration variable. Assuming that the user has selected the Euler method, integration will be performed by calling the following function:

```

1 private void EulerStep()
2 {
3     int i;
4     float sim = integrationStep/particleMass;
5
6     ComputeForces();
7     ComputeCollisions();
8
9     for(i=0; i<num_particles; i++)
10    {
11        velocity[i][0]+=sim*force[i][0];
12        velocity[i][1]+=sim*force[i][1];
13        velocity[i][2]+=sim*force[i][2];
14        position[i][0]+=
15            integrationStep*velocity[i][0];
16        position[i][1]+=
17            integrationStep*velocity[i][1];
18        position[i][2]+=
19            integrationStep*velocity[i][2];
20    }
21    time+=step;
22 }

```

This method executes the four main tasks introduced in section 4.1: line 6 calls the force computation function; line 7 calls the collision detection and response functions; line 9 through 18 perform state integration. More specifically, position, velocity and force are two-dimensional float vectors, whose length is the number of particles in the system. For example, the *i*-th particle is located in 3D space at (position[i][0], position[i][1], position[i][2]).

Figure 4 illustrates an example where a single cloth part is used to simulate a rectangular textured flag subject to wind forces. The

cloth is fixed to a flagstaff by applying a constriction to the position of upper left and upper right particles.

A more complex example is illustrated in Figure 3 and Figure 5 where a complete garment is simulated. This requires to manage the garment seams: the effects of stitching is computed at simulation time, by applying non-linear elastic forces to the different sets of particles that have to be joined, assembling the garment around the virtual body. Figure 3 shows the stitching process of a top on a female body. Figure 5 illustrates the final results of the simulation of the considered top and a skirt.

4.3 System performance

The current version of the system is able to provide real-time simulation on common PCs when the mass-spring system is in the 1000-3000 particles range. For example, the cloth shown in Figure 4 is based on 900 (30x30) particles to which gravity, viscosity, constriction, elastic, and wind forces have been applied: a simulation performed with the Euler method (integration step 4ms) returns acceptable animation frame rates even on low-end PCs, e.g. we obtain 18 fps on a laptop equipped with AMD Mobile Athlon 4 at 1.2 GHz, 256Mb Ram, graphic card S3 Twister 16Mb, using the Cortona 4 player. On the same low-end hardware, the simulation shown in Figures 3 and 5 takes ten minutes (including the stitching phase) before reaching a stable state; the shirt is based on a 2500 particles grid; the skirt on 2500 additional particles, and the body is made of 5000 triangles.

In general, the most computationally expensive task is given by the naive collision detection algorithm, which is the part of the system that needs more improvements.

Figure 7 shows how the accuracy of the simulation can be flexibly changed by setting the resolution of the grid. The upper images (shaded at left, wireframed at right) use a low resolution mesh, allowing for real-time animation even on low-end PCs. The lower images use a higher resolution; aesthetic results improve but computational costs are four times higher.

From the point of view of downloading times on the Internet, it must be noted that the proposed approach allows one to obtain files of minimum size that contain complex animations: this is due to the fact that the animation does not need to be pre-compiled and included in the file. For example, the animated flag illustrated in Figure 4 requires to download only 26Kb (3Kb for the VRML file, 19Kb for the Java class, 4Kb for textures). We made some files available for download at [12].

5. AN INTEGRATED 3D GARMENT PROTOTYPING ENVIRONMENT

A garment has its own 2D geometrical definition stored in CAD files (usually in proprietary formats). This basic 2D data must be complemented by additional information for 3D simulation purposes: for example, traditional CAD systems do not typically include information such as physical properties of the textile materials, textures, and precise seam information among the designed 2D shapes. Some of this information is recorded (after the garment prototyping phase is completed) on paper forms aimed at the different operators involved in the production phase. A complete garment description is thus fragmented along the production process and a significant part of the seams data is not available in electronic format. In this way, the information shared between the prototyping and the production phase is only the one contained in the traditional CAD file.

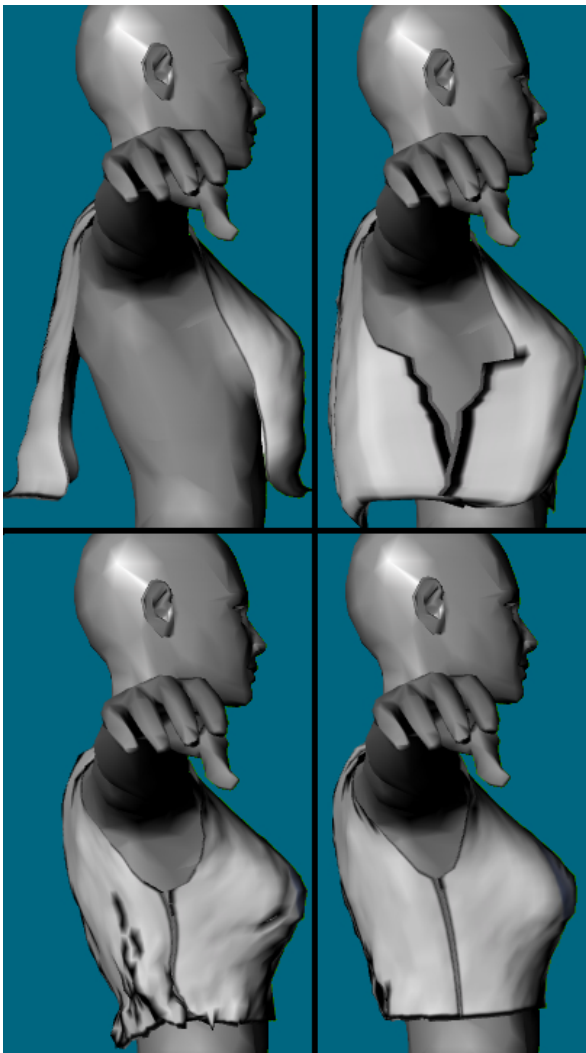


Figure 3. Four stitching phases (This figure is reproduced in color on page X).

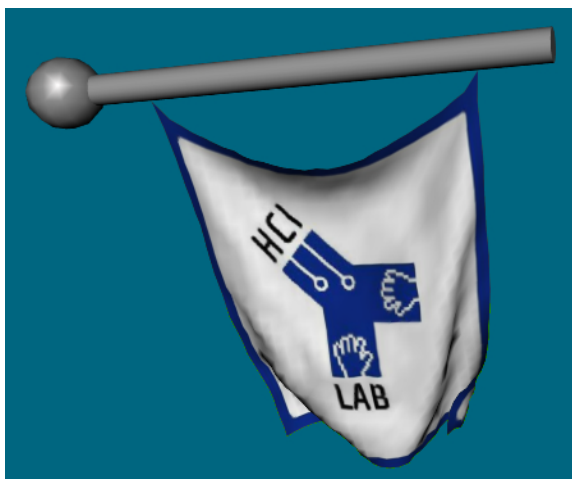


Figure 4. A simulation screenshot: a flag in the wind [12] (This figure is reproduced in color on page X).



Figure 5. Simple garment fits a virtual body (This figure is reproduced in color on page X).

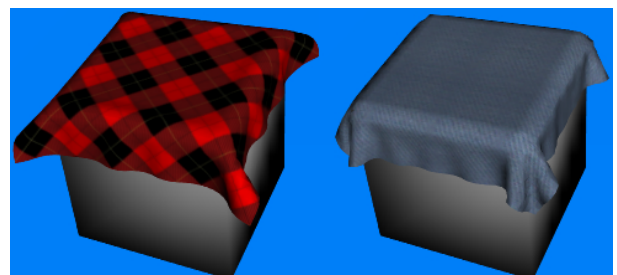


Figure 6. Two different cloth types (This figure is reproduced in color on page X).

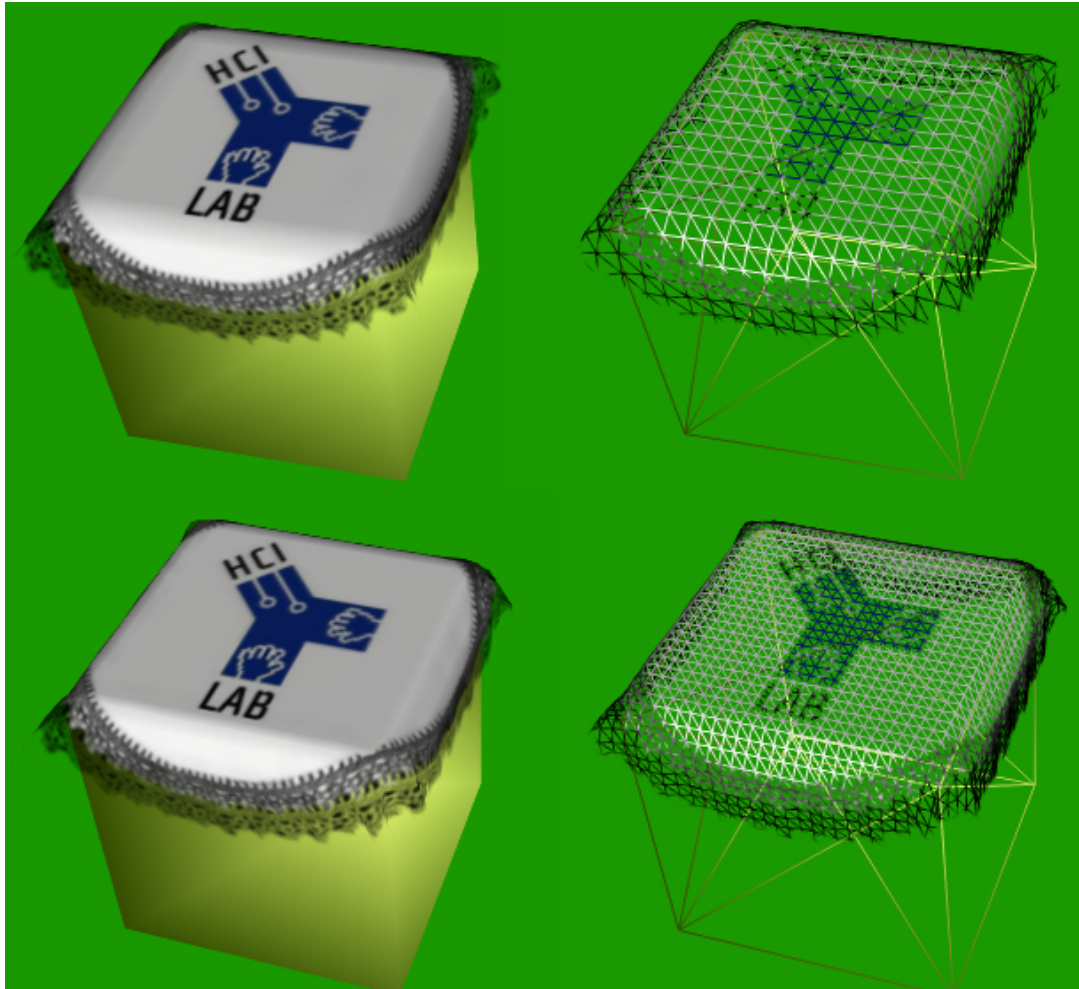


Figure 7. Low mesh resolution (upper images), and high mesh resolution (lower images) [12].

Geometrical information in current CAD files can be directly used by a possible design and simulation tool, but it is not sufficient to build and simulate a virtual garment prototype. The tool should thus take care of representing additional information such as seams, grades, textile types (or properties), colors, accessories. An ideal tool should allow to integrate all the different tasks needed to proceed from concept design to production. To pursue this goal, we have first defined an interchange file format (section 5.1) that can be shared among all tasks; then we developed a tool (section 5.2) able to support the user in defining a complete garment description based on the format, that can be immediately fed into the previously described cloth simulator.

5.1 The XVC (eXtensible Virtual Clothing) interchange format

The final purpose of our XVC format (eXtensible Virtual Clothing) is to collect together and organize all the information needed to represent a garment, including that required for 3D simulation purposes. XVC has been defined in XML. An XVC document is organized in three abstraction layers. The lowest layer is composed by XML entities we call *basicData* and can be of the following types:

- *C2D*: 2D coordinate;
- *C2DSEQ*: sequence of C2D entities;
- *SCALE2D*: 2D scale data;
- *ROTATION2D*: 2D rotation data;
- *COLORRGBA*: color data in RGBA format;
- *SIZE*: garment size data (such as S, M, L, XL);
- *HEM*: data about stitchable areas;
- *PARAMETER*: parameter value (e.g., physical parameters such as weight, elasticity,...);
- *ASSOCIATION*: association between entities (e.g., it can be used to associate a texture to a part of cloth);
- *POSITION*: geometric position data (e.g., it can be used to indicate where a pocket is on a trouser).

These *basicData* entities are assembled into *module* structured entities at the upper level; modules can be of the following types:

- *PATTERN*: geometric definition of garment parts;
- *SEAM*: definition of garment seams;
- *GRADATION*: complete garment grade data;

- *MATERIAL*: data about mechanical textile properties;
- *TEXTURE*: images to apply on patterns;
- *ACCESSORY*: information about buttons or other extras.

Finally, the highest layer is composed by XML entities called *containers*, that are used to assemble *modules* or other containers to define a full garment. For each type of module, there is a container aimed at grouping together different instances of that module: for example, several garment parts (each one represented by a PATTERN module) can be grouped by a PATTERNS container. GARMENT is the top container of the hierarchy, representing the unique root of the XML document. Reasons of space do not allow us to fully describe XVC; in the following, we illustrate it with an example.

A GARMENT container includes an identification number (ID), possibly the format version followed by a number of other containers or modules identified by their IDs. The following is an example of a possible GARMENT:

```
<?xml version="1.0" encoding="UTF-8" ?>
<GARMENT ID="1S001" version="1.0">
  ± <PATTERNS ID="1S001.PATTERNS0">
  ± <GRADATIONS ID="1S001.GRADATIONS1">
  ± <SEAMS ID="1S001.SEAMS2">
  ± <TEXTURES ID="1S001.TEXTURES3">
</GARMENT>
```

Each of the 4 containers in the example includes a number of corresponding modules. For example, if we expand the PATTERNS container, we obtain:

```
<?xml version="1.0" encoding="UTF-8" ?>
<GARMENT ID="1S001" version="1.0">
  ± <PATTERNS ID="1S001.PATTERNS0">
    ± <PATTERN ID="P01" piecename="...">
    ± <PATTERN ID="P02" piecename="...">
    ± <PATTERN ID="P03" piecename="...">
  </PATTERNS>
  ± <GRADATIONS ID="1S001.GRADATIONS1">
  ± <SEAMS ID="1S001.SEAMS2">
  ± <TEXTURES ID="1S001.TEXTURES3">
</GARMENT>
```

where three modules of type PATTERN are identified by their IDs. If we expand one of the patterns we obtain a number of 2D coordinate sequences. The following listing shows an expansion of the P01 pattern and of two of its enclosed coordinate sequences:

```
<?xml version="1.0" encoding="UTF-8" ?>
<GARMENT ID="1S001" version="1.0">
  ± <PATTERNS ID="1S001.PATTERNS0">
    ± <PATTERN ID="P01" piecename="...">
      ± <C2DSEQ ID="C01">
        <C2D x="-31.226" y="0.0" />
      </C2DSEQ>
      ± <C2DSEQ ID="C02">
        <C2D x="-32.347" y="24.307" />
```

```
<C2D x="-33.742" y="48.593" />
</C2DSEQ>
± <C2DSEQ ID="C03">
± <C2DSEQ ID="C04">
± <C2DSEQ ID="C05">
± <C2DSEQ ID="C06">
± <C2DSEQ ID="C07">
</PATTERN>
± <PATTERN ID="P02" piecename="...">
± <PATTERN ID="P03" piecename="...">
</PATTERNS>
± <GRADATIONS ID="1S001.GRADATIONS1">
± <SEAMS ID="1S001.SEAMS2">
± <TEXTURES ID="1S001.TEXTURES3">
</GARMENT>
```

The concatenation of the 2D coordinates contained in a PATTERN allows one to draw a cloth part. Figure 8 shows an example concerning a part of trousers; the upper part of the figure shows the full pattern, while the lower part shows more in detail its geometric definition.

The separation of a pattern in subsequences (C2DSEQ) allows one to identify hems for the garment. This is needed to keep information about seams (in the SEAMS container). An example of a SEAM module is the following:

```
± <SEAM ID="S01">
  <HEM ID="H01" direction="normal" from="C01"
    to="C04" type="normal" />
  <HEM ID="H02" direction="normal" from="C15"
    to="C18" type="normal" />
</SEAM>
```

the module includes a number of HEMs to be stitched together. Each HEM has two attributes (*from* and *to*) that identify sequences of points (C2DSEQ) contained in the PATTERN modules. The other attributes of HEM (*direction* and *type*) are needed to complete the specification of them seam, allowing to assemble the garment.

Parsing and visualizing an XVC document is made easier by resorting to XSL (eXtensible Stylesheet Language). A complete description of the XVC format is provided in [10].

5.2 The VIGDES (VIRtual Garment DESigner) tool

VIGDES (VIRtual Garment DESigner) is a prototype tool that complements the activities usually performed with a 2D textile CAD, aiming at adding the previously mentioned data needed for 3D simulations by relying on the previously described XVC format, and then producing 3D garment previews by exploiting the proposed cloth simulator. The prototype is compatible with existing 2D textile CAD systems, because it is able to import DXF files with the AAMA (American Apparel Manufacturers Association) extension, that is the currently available interchange format for 2D garment data. Finally, the system imports also textures (in jpeg, gif, png, and tiff formats). As shown by the architecture in Figure 9, other main parts of the prototype concern its user interface, whose primary goal is to allow fast data insertion for garment description. Figure 10 shows a screenshot of the interface. It is composed by three main windows: the tree view

of the XVC document (on the left), the graphics window (on the right) and a multi-tab window for data editing and context dialogs (on the lower part of the screen). The tree window allows for object selection and high-level operation (add, delete, copy and paste of XML nodes). After selecting a node on the tree, the user can edit the node properties through a specific edit window. The

graphics window allows for typical 2D CAD operations and specific additional tasks such as stitching. In Figure 10, the user has just completed the specification of seams among 2D cloth shapes (imported from a traditional CAD) and is ready to get a 3D preview of the resulting pair of trousers.

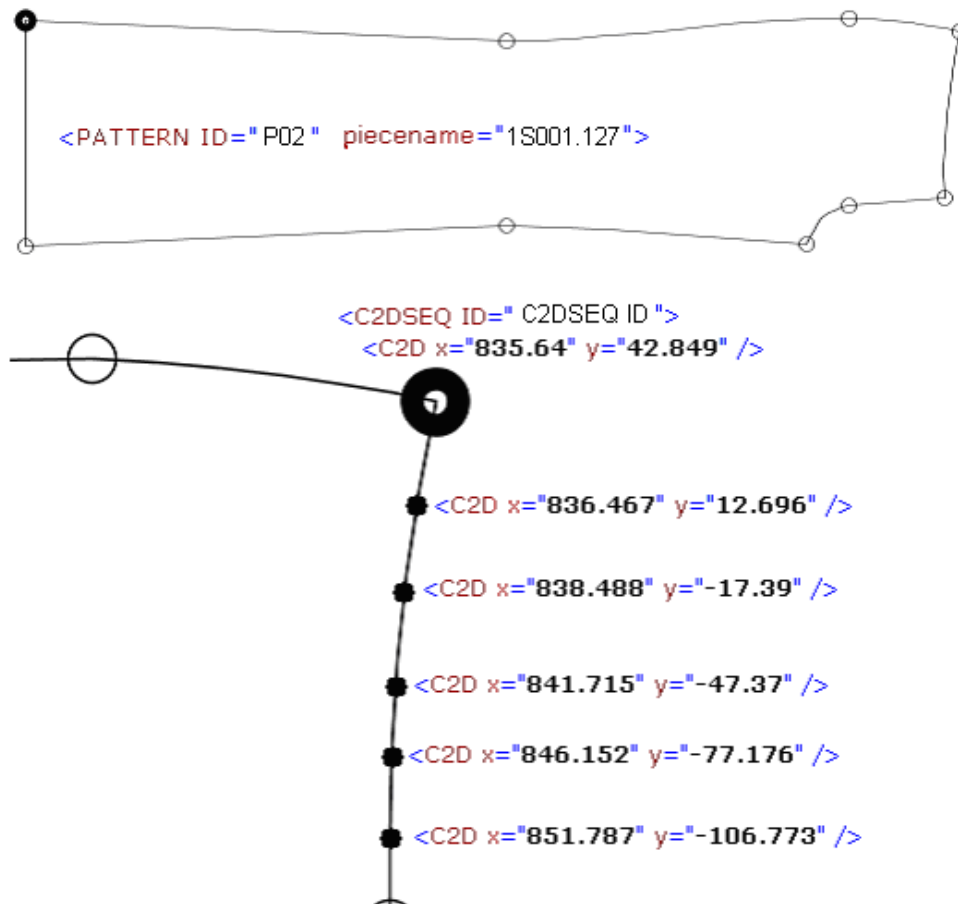


Figure 8. An example of “PATTERN” module, “C2DSEQ” and “C2D” basicData.

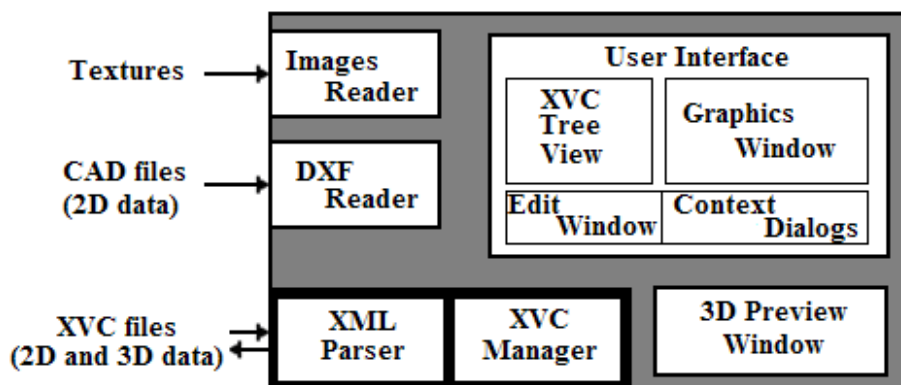


Figure 9. VIGDES architecture.

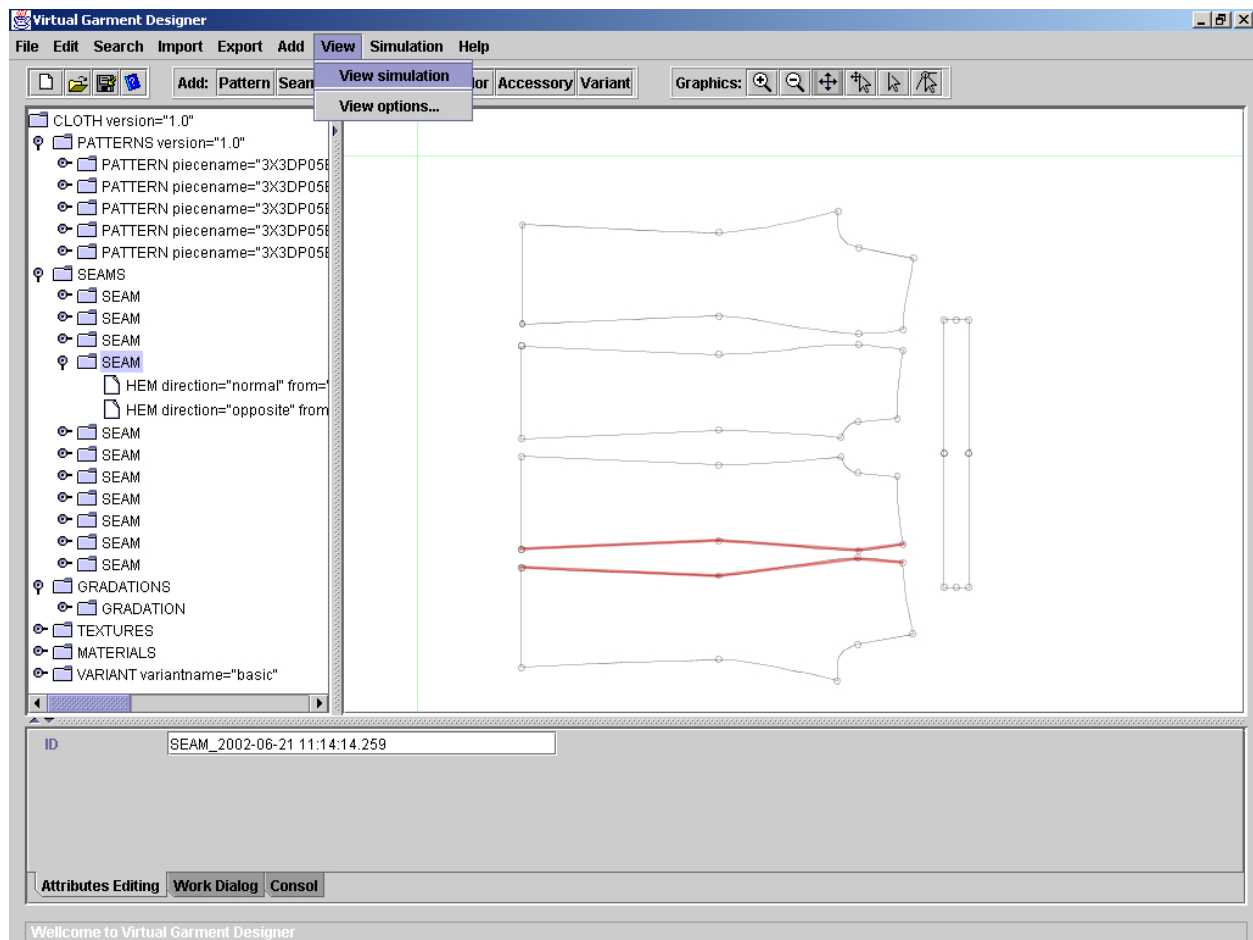


Figure 10. The VIGDES user interface.

6. CONCLUSION AND FUTURE WORK

In this paper, we have presented three main results of our research projects: the Java/VRML cloth simulator, the XVC interchange format, and the VIGDES design tool.

We are currently working at further improving the simulator in two main directions. First, one has to consider that some garment is a complex assembly of different parts (often made of different textile materials) and its structure is sometimes multi-layered (e.g., a pocket stitched on a shirt). The current version of the simulator is instead limited to single-layer, single-material garment. We are thus working on a version of the simulator that independently considers the different textile parts and also the collisions among them. Second, further improvements in efficiency can be gained by changing the current simple implementation of collision detection, and experimenting with new explicit integration methods that have been recently proposed in the field of Numerical Analysis.

From the point of view of aiding the garment designer in easily using our tool, we are working at extending the 3D preview capabilities of VIGDES, by including standard sizing systems used in the textile industry, and parametric mannequins for virtual try-on purposes.

7. ACKNOWLEDGEMENTS

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