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HAPTEX

HAPtic sensing of virtual TEXtiles

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Textile simulation method

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The HAPTEX Project Consortium groups the following Organizations:

ORGANIZATION	SHORTNAME	ROLE	STATE
MIRALab - University of Geneva	UNIGE	Coordinator	Switzerland
University of Exeter	UNEXE	Partner	United Kingdom
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University of Hanover	UHAN	Partner	Germany
Tampere University of Technology	SWL	Partner	Finland

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Table of Contents

1. Abstract

The textile simulation method offers accurate real-time simulation of the nonlinear anisotropic viscoelastic properties of cloth materials. It is used in large-scale simulation of full cloth objects in the context of haptic applications. It combines access to simulation data (particle position, velocity, force and Jacobian) for interfacing with the haptic simulation framework, and collision detection query procedures (detection of cloth mesh elements in proximity of given locations).
The major challenge in the development of this module is to find the best compromise between the high requirement for mechanical accuracy (quantitative accuracy with anisotropic nonlinear strain-stress behavior) and the drastic performance requirements of real-time and interactive applications.

While the visual motion of the global cloth object can be computed with frame rates of about 25 Hz for achieving realistic visual feedback, realistic haptic interaction requires at least 1 kHz for rendering properly the mechanical effect of the user interaction and the force feedback. However, this rendering only needs to be carried out locally, around the haptic contact points. In order to accommodate these requirements, the mechanical simulation is subdivided into two layers: The large-scale layer which is responsible of the global motion of the cloth object, and the small-scale layer which features high-frequency local mechanical simulation for haptic rendering. The textile simulation method addresses the large-scale simulation, while the small-scale simulation is part of the haptic rendering.

All libraries are implemented in standard C++. The development platform is Microsoft Visual Studio 2005 (MS Windows). No graphical front-end is provided in the library releases.

2. Overview

The textile simulation method offers accurate real-time simulation of the nonlinear anisotropic viscoelastic properties of cloth materials. It is used in large-scale simulation of full cloth objects in the context of haptic applications. It combines access to simulation data (particle position, velocity, force and Jacobian) for interfacing with the haptic simulation framework, and collision detection query procedures (detection of cloth mesh elements in proximity of given locations).
While the visual motion of the global cloth object can be computed with frame rates of about 25 Hz for achieving realistic visual feedback, realistic haptic interaction requires at least 1 kHz for rendering properly the mechanical effect of the user interaction and the force feedback. However, this rendering only needs to be carried out locally, around the haptic contact points. In order to accommodate these requirements, the mechanical simulation is subdivided into two layers: The large-scale layer which is responsible of the global motion of the cloth object, and the small-scale layer which features high-frequency local mechanical simulation for haptic rendering. The textile simulation method addresses the large-scale simulation, while the small-scale simulation is part of the haptic rendering.

2.1 Structure

The garment simulation library is made of several modules:

* *The mechanical cloth surface simulation module*

This library implements an accurate mechanical model for simulating the nonlinear viscoelastic properties of fabrics in real-time. It relies on an accurate representation of cloth viscoelastic behavior through polynomial splines for representing weft, warp and shear strain-stress curves. This is integrated into a surface element representation for accurate computation of strain and stress on triangle mesh elements according to the position and force of the mesh vertices, according to the Green-Lagrange tensors. This representation allies the accuracy of finite-element models with the versatility of particle system models.

* *The numerical integration module*

The numerical integration module computes the successive state of the particle system describing the mechanical model along time, through numerical integration of the differential equations that represent the particle behavior. It includes state-of-the-art implicit integration methods that offer robust simulation for arbitrary time-step sizes required by real-time applications.

* *The collision detection layer*

This layer offers support for efficient collision detection queries, and returns the set of cloth mesh elements in proximity to a given set of vertices, up to a specified distance. It implements a bounding-volume hierarchy constructed on the cloth mesh, using Discrete-Orientation Polytopes as bounding volumes.

* *The mesh management layer*

This layer offers automatic construction of rectangular cloth objects, initializing the mechanical and collision libraries adequately. Mesh size and resolution may be specified, along the possibility of constraining surface edges. This layer also acts as an interface between the large-scale simulation layer and the small-scale simulation layer that performs the haptic rendering.

2.2 Implementation

All libraries are implemented in standard C++. The development platform is Microsoft Visual Studio 2005 (MS Windows). No graphical front-end is provided in the library releases.

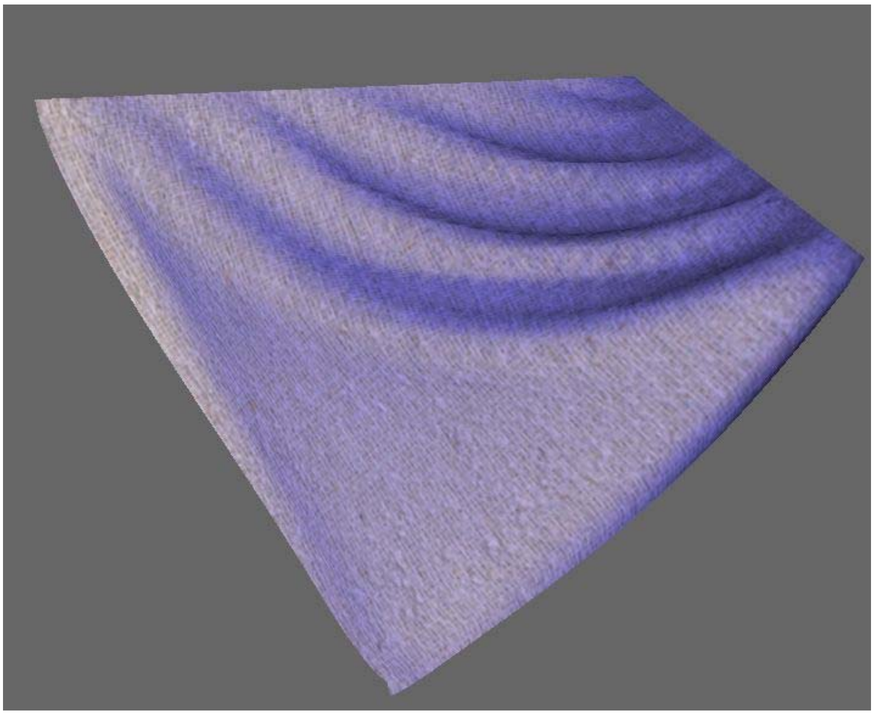


Figure: A piece of cloth simulated in real-time.

3. Detailed Module Description

3.1 Mechanical Cloth Surface Simulation Module

3.1.1 Specifications

The main role of this module is to animate mechanical surfaces described as triangle meshes. These meshes are not necessarily regular and may be obtained through Delaunay triangulation methods. However, we chose the grid representation as the most convenient for parameter and collision detection preprocessing.

The mechanical objects are specified in the form of particle systems (particle position and speed arrays) using triangle elements between these particles as elementary mechanical interactions. Each element carries a set of mechanical properties describing the fabric. These are mainly the density of the fabric, as well as weft-warp-shear strain-stress curves describing the viscoelastic deformation properties of the material. Curves are modeled as segmented polynomial splines described by their interval and coefficients. This allows any arbitrary strain-stress behaviors to be modeled, such as those obtained experimentally from tensile fabric testers (Kawabata, or other more sophisticated strain-stress tests).

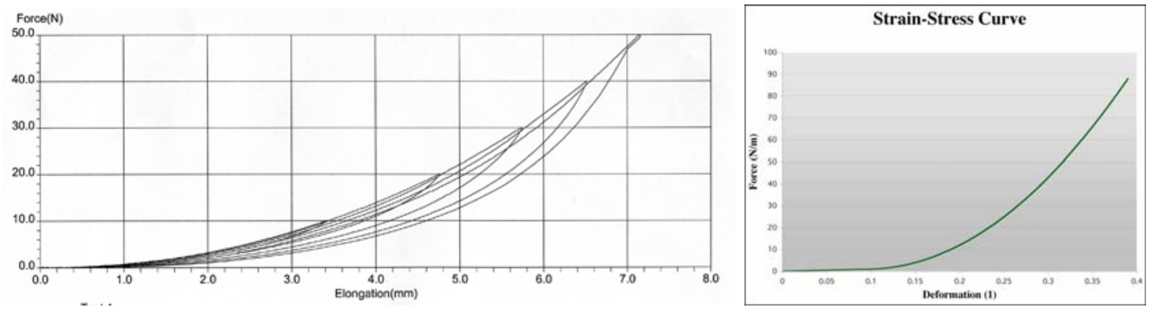


Figure: Typical nonlinear strain-stress behavior measured by tensile testers, and polynomial spline curve model that can be simulated by the library.

Our model ignores plasticity of the strain-stress behavior, as the nonlinear hysteresis model is difficult to characterize accurately and simulate, due to numerical issues resulting from the discontinuity of the equations. This is not much an issue as this plasticity does not influence much the draping, but rather the dissipative behavior of cloth motion, a phenomenon that can be simulated through viscosity that our model supports.

Bending stiffness is not simulated by the large-scale model, mainly because through the large size of the mesh elements, bending forces are usually too small to have any significant effect. Therefore, the expected wrinkle size of the cloth is more likely to be limited by the natural stiffness of the surface mesh (tensile mesh stiffness creates bending rigidity), than the expected amount of native mechanical bending forces. Bending stiffness models also require a significant amount of computation which may be an issue in real-time applications. Indeed, bending effects will be taken into account indirectly, through the effect of the small-scale model which considers it for the haptic rendering.

The library supports additional external forces, such as gravity weight and aerodynamic wind drag. These effects play an important role in draping and motion dissipation.

External user-defined forces and interactions may also be defined. This is necessary for the integration of collision effects between the cloth and haptic mechanical response models. Geometrical constraints may also be enforces through direct action on the object state (correction of particle positions and speeds). Cloth objects can be attached in this way to fixed or moving locations.

3.1.2 Research and New Developments

The major challenge in the development of this module is to find the best compromise between the high requirement for mechanical accuracy (quantitative accuracy with anisotropic nonlinear strain-stress behavior) and the drastic performance requirements of real-time and interactive applications.

The mechanical model takes advantage of a surface-based particle system that follows many of the properties initially found in finite elements [IRV 04]. Basically, the system evaluates the strain of each triangle element according to the position and speed of the particles, then uses the mechanical properties of the material for computing the stress of the elements, and converts back the stresses into equivalent particle forces [VOL 05].

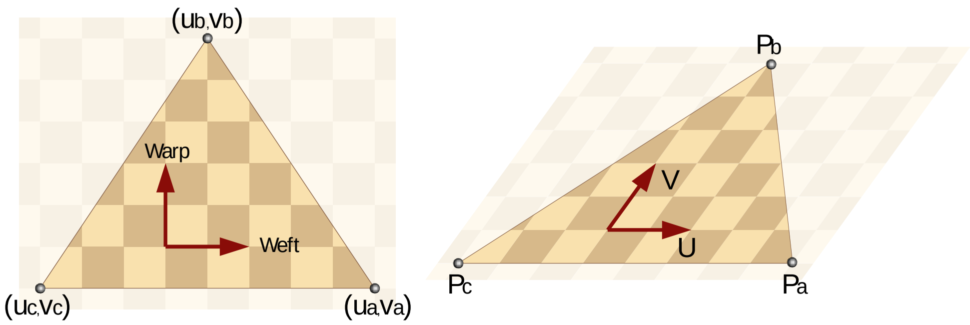


Figure: The model is based on accurate strain-stress evaluation on triangle elements using the nonlinear Green-Lagrange tensor.

While this scheme has strong analogies to first-order finite elements, we have however carried out some developments aimed at vastly improving the computation speed without too many sacrifices in the accuracy. Among these developments, computational simplifications are obtained by avoiding the computations required for the linearization of the strain and stress tensors [ETZ 03]. This has led to the formulation of a very simple and efficient particle system computational procedure that can be integrated by any of the numerous high-performance numerical solvers. Furthermore, an adapted accurate computation of the Jacobian is implemented for ensuring numerical stability even is very severe deformations [CHO 02].

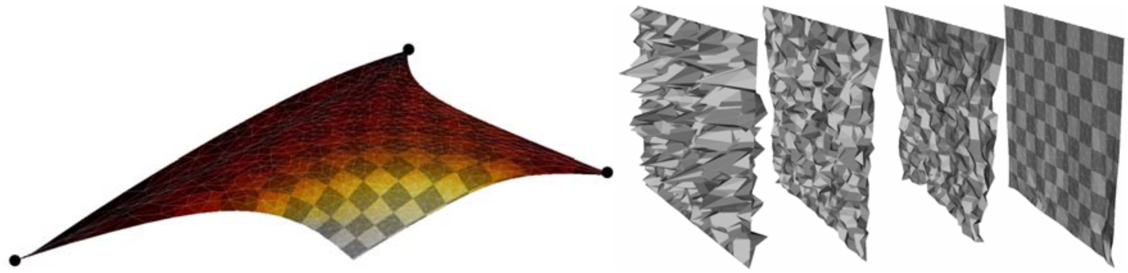
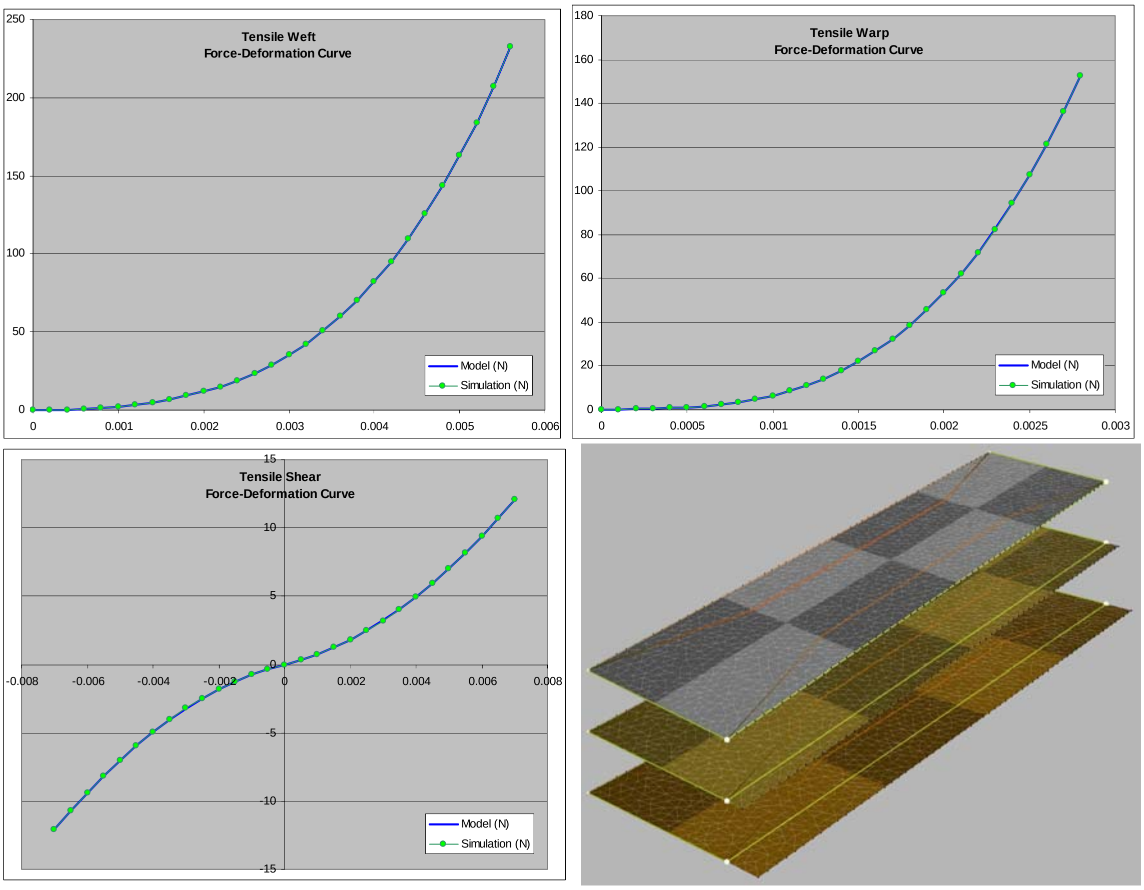


Figure: Stability tests on extremely deformed objects, and numerical convergence tests.

The main interest of this computational process is to offer very good computational performance while handling materials that possibly have nonlinear and anisotropic strain-stress laws, with accuracy in par with finite-element models. Yet, our system offers all the performance and flexibility related to particle systems, particularly trough the possibility of handling directly geometrical constraints such as collisions.

3.1.3 Results

Thanks to the accurate formulation of strain and stress computation, the model is able to reproduce arbitrary tensile strain-stress curves with a very high accuracy. We have tested the accuracy of the model through a "virtual tensile test" that compares the force-displacement behavior resulting from the theoretical strain-stress curve described by the polynomial spline model to the force virtually measured on the tensile test of a cloth sample of 2500 elements. The chosen material behavior corresponds to an "average" cloth material that exhibits typical strain-stress behavior.



From these curves, we can see that the force-deformation behavior our simulation system duplicates exactly the force-deformation model resulting strain-stress polynomial spline model (converted back to force-deformation). The error remains always well below 0.01N whereas total forces may exceed 100N. This illustrates the very high accuracy that our model can provide even in the context of nonlinear anisotropic materials in the context of large deformations. Such accuracy is indeed expected, since our model represents accurately the mechanical constitutive laws of the material without any approximation.

3.2 Numerical Integration Module

3.2.1 Specifications

Through the particle-system formulation of the mechanical model, the library computes successively the evolution of the particle positions and speeds in user-specified time steps, which do not need to be uniform (this is a requirement for real-time systems).
The library should also fulfill the very high robustness requirements of real-time applications, mainly related to the fact that the simulation should not crash whatever any possible animation context of the body (possible position jumps and other not-so-

realistic motions resulting from possible low frame rates and poor-quality haptic motion capture).

3.2.2 Research and New Developments

Numerical integration is another key issue to fast and efficient particle systems. While explicit methods guarantee dynamical accuracy at a very high computational time usually incompatible with real-time applications, implicit methods allow moving the trade line toward much higher computation performance at the expense of accuracy.
In the context of real-time simulation, high-performance solvers [EBE 00] [HAU 01] [VOL 01] now focus on implicit methods for attaining the performance required for interactive models [COT 99] [JAM99] [HAU 03] [MEY 01] [MUL 00] [MUL 02]. However, their computational speed is obtained either through large compromises on the accuracy which, for low-order methods, affect the dynamic cloth motion realism through numerical damping, and for high-order methods, compromise the stability.
We did not retain the BDF-2 method [HAU 01], as this 2nd-order method might exhibit stability issues under severe deformation conditions particularly when dealing with highly nonlinear mechanical behaviors (collisions). Instead, adaptations of the simple Backward Euler method [VOL 01] seem to offer the best unconditional stability that is really necessary in the context of real-time applications. Meanwhile, accuracy can be significantly improved through the use of the Backward Midpoint variant [VOL 05].
Further investigations are being carried out for improving even more the performance and accuracy of the mechanical simulation. For instance, new fast linear bending simulation scheme [VOL 06] is being investigated for adding realism to stiff cloth materials. Other context-specific enhancements deal with the simplification of the mechanical context when collisions are the most determinant factor in the motion of cloth areas.

3.2.3 Performance

Performance has been evaluated by simulating the drape motion of squares of fabrics, attached horizontally along one of their edge, and moving freely under the effect of gravity.
For real-time computation of the animation, and using linear stain-stress laws, the total frame rates (which include mechanical computation as well as OpenGL rendering) are the following:

Computational data: 50 cm x 50 cm cloth square, 0.1 kg/m2, 100 N/m linear isotropic elastic modulus, real-time time-stepping.

* *1000 polygons: 80 fps.*
* *2000 polygons: 35 fps.*
* *5000 polygons: 12 fps.*
* *10000 polygons: 5 fps.*

The use of nonlinear elastic strain-stress laws roughly slows down the computation by a factor of 1.4. Therefore, it is reasonable to think performing real-time full accurate mechanical computation of a piece of cloth with a mesh polygon count up to 2000 triangles. Meanwhile, interactive applications might handle up to 10000 triangles.

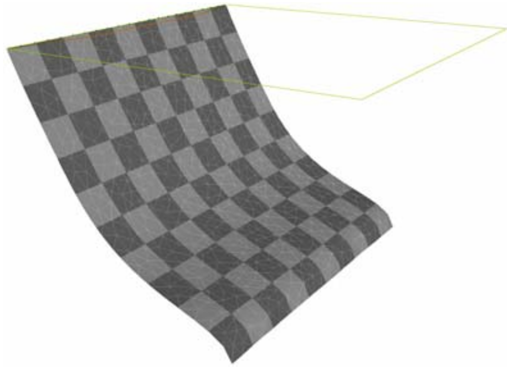
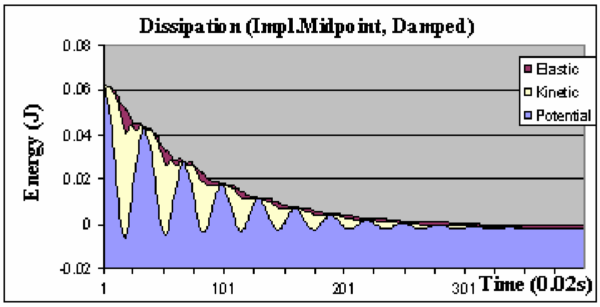



Figure: The drape performance test, and the resulting energy dissipation curves.

The accuracy of the computation is highly dependent on the mesh element size, the stiffness of the strain-stress laws, the mass and the actual computation time-step. Dynamic accuracy can be evaluated by measuring the mechanical energy dissipation resulting from numerical damping along an animation. It can be improved through time-step subdivision, at the expense of computation time.

3.3 Collision Detection Layer

3.3.1 Specifications

The aim of this layer is to provide tools for detecting efficiently the mesh elements involved into haptic interaction. The result of this query is then used by the haptic rendering layer to process the interaction between the piece of cloth and the haptic device.
The module should detect the mesh elements in a neighbourhood of the haptic cursor. Different representation enveloping the haptic cursor could be used: a point, one or several spheres, and a volume bounding two points or two spheres. A state of the art algorithm should be used in order to meet real time requirement and as usual with this specification a solution being a tradeoff between accuracy and speed should be found. Literature was reviewed to answer our needs.

3.3.2 Research and New Developments

Collision detection is a wide and old field in Computer graphics starting with the collision between rigid bodies with more interest over deformable models those last years [TES05]. Our layer only deals with the detection of collision and more especially on proximity query, special sub domain are not taken into account such as self collision detection due to real time constrains and collision responses feed by the small scale deformation module.
During the run time of the simulation, no topological changes are made so the hierarchy of the bounding volume is constructed recursively at the mesh generation. A binary tree is generated with a top down approach with the first level containing the whole textile, the second level a half of the textile and so on. The data of the bounding volumes are updated using a bottom up scheme from the leaf to the whole textile.
The collision tests are then made between the representation of the haptic cursor and the tree of bounding volume. The hierarchy can be seen on the following figure with the full hierarchy on the right and the list of successive colliding volume on the left.

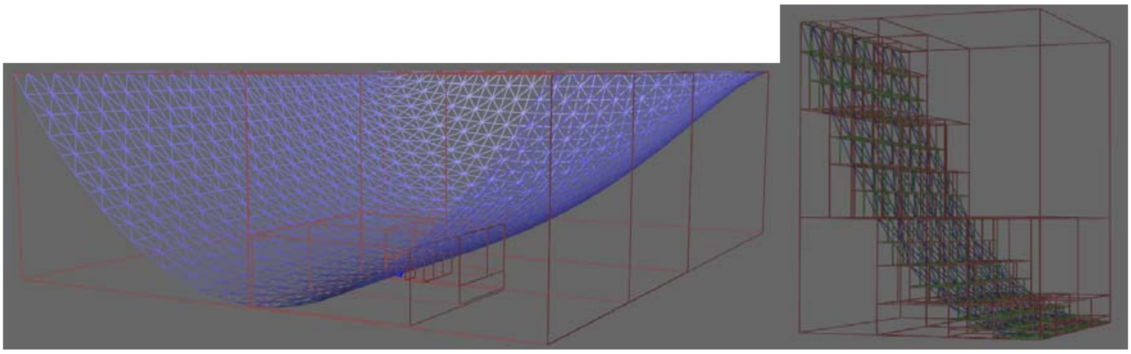


Figure Bounding volume hierarchy of a cloth mesh.

The possible bounding volumes that could be used were k-discrete oriented polytopes (k-dop), axis aligned bounding boxes (AABB), sphere, Oriented Bounding boxes (OBB). The difference between the bounding volumes is mainly in terms of accuracy and computation speed, the volume bounding the object tighter are the more expensive to compute, the AABB are the larger volume while k-dop are the tighter. Basically, the AABB is a cube, it bounds the object along three axes: x, y, z, and more axes can be added, for example for 14 dop, there is the previous axes and x+y+z, x+y-z, x-y+z and x-y-z. A 26 dop was used as a bounding volume because using a volume this tight doesn't introduce a large overhead in our case due to the relatively small number of polygons present in simulation.

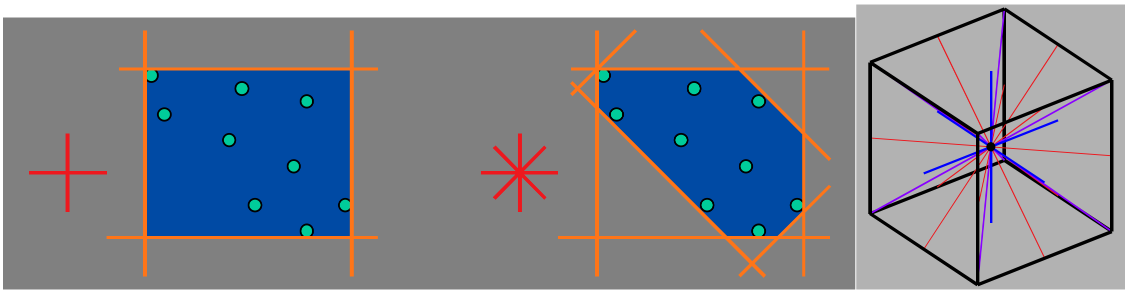


Figure: Discrete Orientation Polytopes are constructed as a generalization of bounding boxes, with additional bounding directions along the diagonal directions of a cube.

The output of the collision detection query can be seen on the following figure displaying in red the volume bounding mesh element in a given boundary

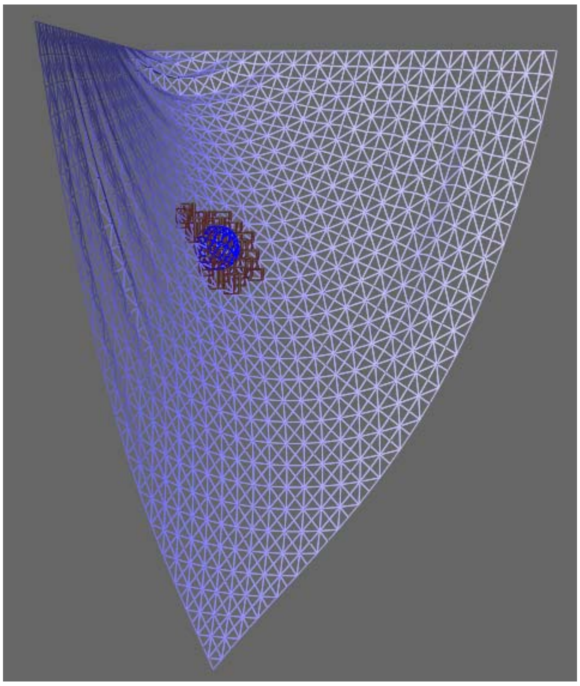


Figure: Proximity detection between a haptic contact point and the cloth surface mesh.

3.4 Mesh Management Layer

The construction of the mesh is augmented through several levels. At the ground level a mesh is build with the specification of the size in meter and number of particles. On the next level, the basement for collision detection is added with the generation of the hierarchies of bounding volumes and the support for proximity query and updates of the data. Finally the last level is concerned with the integration of the mechanical simulation with the computation of the deformation, the ability of include and exclude particles and the affectation of materials.
All those parameter can be updated in run time as you can see on the screenshot of the application. Here the rendering is done using opengl and the graphical user interface is with MFC. Furthermore an additional layer gives the ability to send an external force within the model to emulate the action of the haptic interaction.

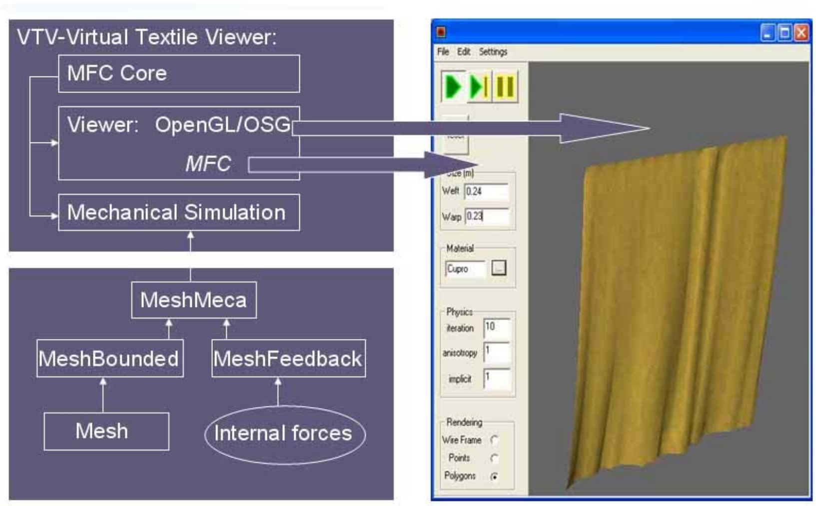


Figure: Structure of mesh layer and application screenshot

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