Cloth Modeling with a Discrete Cosserat Surface

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***Abstract*—The two main sheet-based paradigms in the simulation of cloth modeling are mass-spring particle systems and models using continuum mechanics. The first one can produce good and fast visual representations, but lacks explicit relations with the real physical attributes of the cloth, while the second is usually too slow to produce real-time results. We are researching a GPU-based numerical solution for a cloth model that is based on continuum mechanics and has realism close to the yarn-based model.**

***Keywords*-Cosserat Surfaces; Cloth animation; GPU-based implementations.**

I. Introduction

Cloth modeling is of particular interest in several applications, ranging from the entertainment and advertisement purposes to the highly lucrative fashion business. Although a variety of strategies for the computer support of cloth modeling and animation has been rapidly evolved since the mid seventies, realistic cloth modeling is still a challenging problem both for the graphics and for the textile engineering communities. Fabrics are complex structures consisting of interwoven threads, which are themselves made of twisted fibers. The frictional (internal) forces between these fibers give the fabric a very peculiar physical behavior under applied (external) forces. It strongly resists to the length/area variations while being very permissive to bending deformations, such that wrinkles and buckles form and disappear naturally under pure compression forces, that is the shrinking or contraction forces that lie on the cloth surface and are perpendicular to the direction of small ridges formed on a surface.

Despite impressive visual results achieved by Kaldor et al. [1] with yarn-based models, we still look for an improved sheet-based model because of its efficiency and vast applicability, such as plain-woven fabric and human skin simulations. There are essentially two sheet-based models: the particle or mass-spring paradigm, in which a fabric is considered as a collection of material points held together by structural, shear and flexion springs for simulating its material mechanics properties [2]–[4]; and the continuum mechanics based technique, in which a fabric is regarded as a continuous media to which the nonlinear thin shell or thin plate theory is applied for analyzing its stretching, shearing, and bending/flexural behavior [5]–[7]. It is worth remarking that, after spatial and time finite differentiations, the particle and the continuum approaches have similar ordinary differential formulations. They differ essentially in the *constitutive equations*, which are responsible for the internal force due to the cloth deformation.

In this project we give contintuity to a research on the bending model that is founded on continuum mechanics – the theory of a Cosserat surface, which is considered as a geometrically exact shell model [8]. Two properties of this model were decisive in our choice. First, this model represents the cloth dynamics, taking into account the compatibility between the stretching and bending measures. Thus, the wrinkles can be naturally formed without resorting to data-driven techniques [9]. Second, the analogy between the statical (contact forces and couples) and the geometrical quantities (stretching and bending measures) may be easily established, which facilitates the design of a “what you control is what you get” interface, one of the main flaw of the current physically based simulations [10].

This model, however, poses challenges to the real-time implementation. Its non-linear formulation is not very conducive to numerical implementation for a mesh with arbitrary topology, much less to be applied on discrete samples.

II. Cosserat Surface

According to Cosserat surface theory the *cloth's stiffness* of each sample $\mathbf{r}(t)$ at a time instant t may be expressed as a function of the variation of the internal energy $\mathcal{A}(\mathbf{r}, t)$ to the stretching measures ε (variations of metric tensors with respect to the initial state) and to the bending measures κ (variations of curvature tensors with respect to the initial state):

$$K(\mathbf{r}, t)\mathbf{r}(t) = \mu \frac{\delta \mathcal{A}(\mathbf{r}, t)}{\delta \mathbf{r}(t)} = \frac{\partial \mathcal{A}(\mathbf{r}, t)}{\partial \varepsilon(t)} + \frac{\partial \mathcal{A}(\mathbf{r}, t)}{\partial \kappa(t)}. \quad (1)$$

Plugging it into the partial differential equilibrium equation [5], we get

$$\mu \frac{\partial^2 \mathbf{r}}{\partial t^2} + \varrho \frac{\partial \mathbf{r}}{\partial t} + \mathbf{K}(\mathbf{r}, t)\mathbf{r}(t) = \mu \mathbf{F}(\mathbf{r}, t) \ , \quad (2)$$

where μ is the mass density (mass per unit area), ϱ is the coefficient of the damping forces that counteract the intrinsic textile frictions and the external fluid frictions, and $\mathbf{F}$ denotes the total contribution of external forces per unit mass on $\mathbf{r}$.

Figure 1 presents the iterative simulation data flow. Starting from a sampled surface, we compute for each sample at t the surface tensor components $N^{i\alpha}$ and $M^{\gamma\alpha}$ from the derivatives of the metric ($a_{\alpha\beta}$) and the curvature ($b_{\alpha\beta}$) tensors. Then, we calculate the internal forces given in Eq. 1, which are equivalent to the covariant derivatives $\mathbf{N}^1_{|1}$ and $\mathbf{N}^2_{|2}$. Substituting them in Eq. 2, we get the sample point's acceleration $\dot{\mathbf{v}}(t)$ and velocity $\mathbf{v}(t+\Delta t)$. This allows us to obtain the sample position at next time instant $t + \Delta t$. Successively, we get a series of mesh evolving forward in time under physical and geometrical constraints that creates the illusion of cloth animation.

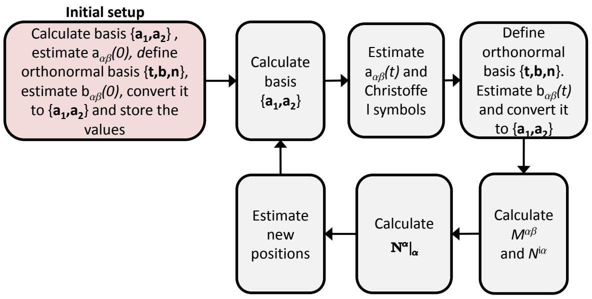

Fig. 1. Simulation data flow.

III. Problems and Challenges

Implementation on CPU: In this stage we aim at assessing the feasibility of solving Eq. 1 locally for each sample and Eq. 2 with explicit numerical integration method. The most challenging issues we are addressing in this stage are the specification of appropriate boundary conditions and the estimation of cloth's stiffness without resorting to a large number of simultaneous algebraic equations (implicit integration) in order to make it as easy as possible to parallelize.

Implementation on GPU: This stage consists in migrating our CPU-solution to GPU aiming to improve on the highly parallelizable implementation provided by the CPU-solution by moving each step described in Figure 1 to the GPU and executing them concurrently for each vertex. To do this, the main points we need to pay attention to are: the memory usage, how to organize the multiple vertex neighborhood data needed to solve the equations numerically for an arbitrary mesh and the bottleneck posed by the data exchange between CPU and GPU.

IV. Preliminary Results

A. Implementation on CPU

Aiming at real-time realistic cloth simulations, we realized a series of attempts to implement Eq. 1. Because the solution involves several steps that do not have off-the-shelf codes, we have assessed each step before the integration. Figure 2 illustrates the results that we have already achieved: an animation of a mesh with vertex valence between 4 and 8 encoded in a half-edge data structure. On this mesh, we apply an external force in a restricted region, or gravity on all vertices.

B. Implementation on GPU

For now, the metric and curvature tensors estimation is being migrated to the GPU, using OpenCL. This first implementation already contemplates a solution for the data structure problem that uses two vectors for vertexes and normals and one for the vertexes' neighborhood that contains offsets to the other two. We are still studying the possibility to implement the half-edge data structure in OpenCL. Optimization is also being addressed by trying to minimize the accesses to the GPU's global memory by keeping as much as possible in the local memory. We are currently testing this solution to assess its correctness and the optimization gain over the CPU-solution.

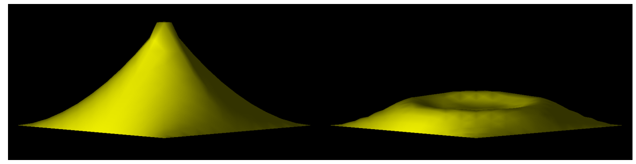

Fig. 2. Simulation of streching the cloth and letting go, without gravity

V. Conclusion and Further work

We have proposed a discretization of the Cosserat Surface theory to model simulations of cloth movements as a way to produce more realistic animations when compared to the mass-spring models, but without the heavy computational costs of the traditional continuum mechanics models. We could produce real-time simulations for meshes of size 20x20. However, the first stages described in Figure 1, are already being migrated to a GPU solution, and the other stages can also be migrated, which should enable us to produce real-time simulations for meshes of greater sizes. We are also working on a solution for the limitation regarding the border regions so that more complex surfaces can be simulated.

Acknowledgment

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