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Toward Estimation of Yarn-Level Cloth Simulation Models

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Abstract

Efficient and realistic cloth simulation is an unsolved problem, with yarn-level models emerging as a new alternative thanks to new hardware capabilities. Modeling yarns as flexible rods with persistent contacts enables a very robust and efficient simulation. However, this assumption also complicates the definition of elastic deformation potentials. This work explores more accurate yarn-level cloth models together with experiments that compare model features in order to detect shortcomings in the persistent contact model. In particular, we have implemented a discrete elastic model of flexible yarns with contact which treats yarns as unidimensional splines, together with a model that discretizes yarns using three-dimensional finite elements.

CCS Concepts

•***Computing methodologies*** → *Physical simulation;*

1. Introduction

In the cloth manufacturing industry, having a virtual preview of a garment during the design process could reduce the number of iterations until the prototype is released. In other industries, like film or video game industries, a realistic cloth behavior leads to more expressive and engaging characters. For these reasons, cloth simulation has been studied thoroughly since the beginnings of computer animation.

Modeling cloth using yarns emerged as a way to improve the visual appearance of cloth simulations. Kaldor et al. [KJM08] were the first to demonstrate the capability of simulating real knitted fabrics at the yarn level. They used an inextensible yarn model where motion is solved with the well-known Newton's second law, using the derivatives of potential energies to compute forces. The bottleneck in their method is collision checking, which requires testing and handling collisions for many small spheres that cover the yarns.

Later on, Cirio et al. [CLMMO14] developed a novel model for woven cloth simulation, where contact is persistent at yarn crossing points, and additional degrees of freedom model sliding between yarns. Their model produces results of higher resolution at lower cost, as it avoids the need for explicit contact handling. Unfortunately, the model by Cirio et al. uses simplified definitions of the internal forces of yarns, and fails to capture all the nonlinear and interaction effects at yarn scale.

The purpose of this paper is to explore tools that will help improve the force definitions of the persistent contact model, retaining its computational benefits while achieving higher accuracy. We have developed two models of increasing complexity, which represent yarn-yarn interactions explicitly:

- A discrete elastic curve model with yarn-yarn contact handling, similar to the one by Kaldor et al. [KJM08, Kal11]. In contrast to their work, our yarns can stretch, to model also extensible yarn materials, and we solve dynamics using implicit integration.
- A volumetric, continuum-elasticity model of yarns, discretized using finite elements (FEM). To this end, we have relied on the commercial program ANSYS LS-DYNA.

These two models will help us in two ways. First, they will allow us to identify the limitations in the persistent contact model. Second, they will provide data for example-based estimation of more complex force models, e.g., based on strain-domain interpolation of energy functions [MMO16]. Even though the FEM model will provide superior accuracy and richer data for parameter estimation, it is unclear whether it will be tractable for mid-scale experiments involving hundreds of yarns. Therefore, the elastic curve model with contact provides a model of intermediate complexity and accuracy, which might enable progressive estimation.

2. Related work

The most common approach for computer animation of cloth is to approximate the fabric as a 2D elastic sheet. Terzopoulos et al. [TPBF87] employed elasticity theory to build continuum models, while Baraff and Witkin [BW98] introduced a discrete model based on constraint energies, and designed a simulation algorithm that allows larger time steps.

As mentioned in the introduction, Kaldor et al. [KJM08] pioneered yarn-level cloth models in computer graphics. They developed a yarn-level model for knitted cloth which was able to simulate different fabrics with a realistic yarn count. Yarns are modeled using B-splines, with the curved shape governed by control

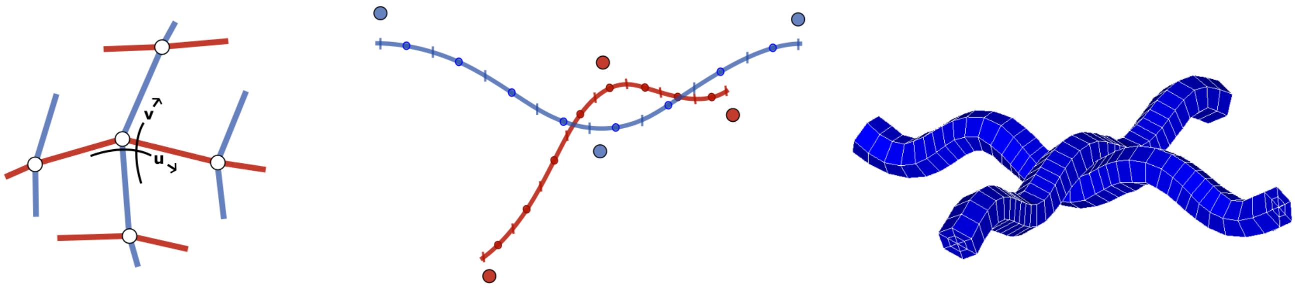

Figure 1: ***Left:*** *Persistent contact model introduced by [CLMMO14]. Degrees of freedom are placed at yarns crossings, which can both translate in space and slide along yarns in contact.* ***Center:*** *Flexible curves with contact handling, similar to the model introduced by [KJM08]. Control points, represented with bigger circles, govern the shape of B-splines that compose the yarns. Smaller points are integration points for the evaluation of energy functions.* ***Right:*** *Volumetric yarns modeled using FEM. The degrees of freedom corresponds to the nodes, placed at the corners of blue elements. Energy is computed per element, using eight integration points.*

points q. The 3D spatial coordinates of these control points define the degrees of freedom of the dynamic system, as depicted in figure 1-center. Yarns are modeled as inextensible due to their high resistance to stretching, while other intra-yarn and inter-yarn forces are computed as the derivatives of energy potentials. Then, yarn dynamics are formulated as constrained Lagrangian dynamics, and solved using an explicit integration method with the implicit constraint projection method described in [GHF*07].

Cirio et al. [CLMMO14] proposed a planar model for woven cloth where inter-yarn contacts are modeled as persistent contacts, with additional degrees of freedom to allow sliding. This model creates a contact node at every yarn crossing. Therefore, contact nodes exhibit three Lagrangian plus two Eulerian degrees of freedom, representing the 3 spatial coordinates and 2 sliding coordinates respectively, as shown in figure 1-left. The internal forces include stretch, bending and shear, with friction modeled using a penalty-based approximation of the Coulomb model. Dynamics are formulated using Lagrangian mechanics, and integrated in time using backward Euler implicit integration.

Both the models of Kaldor and Cirio represent yarns as twist-free flexible rods. Other works in computer animation also attempted to simulate one-dimensional objects using elastic rod theory. Remion et al. [RNG99] developed a method for simulating the dynamics of one-dimensional curves using splines with control points as the degrees of freedom of the spline. Spillmann and Teschner [ST07] presented a deformation model called CoRdE, based on Cosserat theory with efficient contact handling. Bertails et al. [BAC*06] used helical rods governed by Lagrangian mechanics to design a robust solution for hair animation. Bergou et al. [BWR*08] presented a discrete model that handles twist and centerline dynamics separately.

Cloth has also been studied in the field of textile engineering using a FEM approach. For example, Liu et al. [LCS*17] performed a three-dimensional analysis in order to capture nonlinear geometric effects in knitted fabrics. This work was recently extended [LSD*18], comparing the results with a one-dimensional discretization vs. the computationally more expensive three-dimensional discretization.

3. Flexible yarns with contact handling

The model by Kaldor et al. [KJM08] is the simplest yarn-level model that accounts for contact effects explicitly. In contrast to the persistent contact model, which accounts for them implicitly, it models internal forces that capture the relative motion and deformation of yarns at yarn crossings. For instance, in a woven fabric, if yarns in one direction are stretched, they will tend to get straight, while yarns in the perpendicular direction will tend to adapt their curvature to this new configuration. As this kind of effects are currently not handled in the persistent contact model, a yarn model with contact handling could help estimate appropriate energy models for the persistent contact model to reproduce these effects.

We have extended the model of Kaldor et al. by introducing yarn extensibility, and thus supporting a wider range of yarn materials. We borrow the B-spline discretization and their energy formulations, and add a stretch energy term. We also propose implicit Euler numerical integration to handle the numerically stiff equations produced by stretch energies. This integration method requires the solution of a linear system and the assembly of energy Hessians (second-order derivatives of energy potentials).

B-splines: Yarns are represented as 1D B-splines, using the positions of control points as the degrees of freedom of the mechanical model. In addition, each yarn is divided into equidistant intervals with respect to the intrinsic coordinate s along the spline. For the evaluation of energy terms, we place an integration point in the center of each interval. This discretization is shown in figure 1-center.

Dynamic model: The dynamic behavior of yarns is modeled using Newton's second law, computing forces as the negative gradients of potential energy and dissipative potential as in equation 1.

$$M\ddot{q} = -\nabla_q E - \nabla_{\dot{q}} E \tag{1}$$

where M is the mass matrix, q, $\dot{q}$ and $\ddot{q}$ are respectively positions, velocities and accelerations arrays of the degrees of freedom, $E = U(q)+D(\dot{q})$ is the sum of the potential energy of the system and the damping modeled as a dissipative potential, and $\bigtriangledown$ is the gradient operator which derives the potentials with respect to positions or velocities. Our energy model is composed of individual energies to capture the different intra and inter-yarn effects.

Energy model: The total energy E of the system is computed from an energy density e along the yarn. The expression is first defined in the continuum yarn and then the yarn domain is discretized into intervals, where energy density is considered constant:

$$E = \sum_{y=0}^{Y} \int_{0}^{1} e_y(s)ds = \sum_{y=0}^{Y} \sum_{i=0}^{I} e_y(s_i) \tag{2}$$

where Y is the number of yarns in the system and I is the number of intervals that discretize the yarn.

$e_y(s_i)$ denotes the total potential and dissipative energy assigned to a specific interval, which can be decomposed into the sum of the following energy terms: stretch, bending, gravity, collision with external elements, global damping and friction. We refer to [KJM08] for the expressions of these energies, except for stretch.

To model stretch, we deviate from the inextensible model of Kaldor. Stretch is the internal energy of yarns that resists length changes under external forces along the centerline. It is modeled for a specific interval as follows:

$$e^s(s_i) = \frac{1}{2} K_s\, l(s_i) \left(\frac{||y'(s_i)||}{||y'_0(s_i)||} - 1 \right)^2 \tag{3}$$

where K_s refers to the stretch stiffness, $l(s_i)$ the length of the interval, $||y'(s_i)||$ the position derivative at the integration point with respect to the intrinsic coordinate that travels the yarn, and $||y'_0(s_i)||$ the same position derivative in rest state. The value in parenthesis measures the local relative stretch of the yarn with respect to its rest state.

Time integration: We use an implicit Euler method to integrate the positions of control points and compute the state of yarns in the next time step. Starting from equation 1 and applying the implicit time-discretization followed by force linearization, the velocity and position in the next time step t_h can be expressed in terms of the current time step t as:

$$\begin{cases} \left(M + t_h C(t) + t_h^2 K(t)\right) \dot{q}(t+t_h) = (M + t_h D(t))\, \dot{q}(t) - t_h F(t) \\ q(t+t_h) = q(t) + t_h \dot{q}(t+t_h) \end{cases} \tag{4}$$

where $C(t) = \dfrac{\partial^2 E}{\partial \dot{q}^2}$, $K(t) = \dfrac{\partial^2 E}{\partial q^2}$ and $F(t) = \left(\dfrac{\partial E}{\partial q} + \dfrac{\partial E}{\partial \dot{q}} \right)$.

In our implementation, we compute energy derivatives using finite differences. The mass matrix is computed by distributing the mass of intervals to control points according to the basis functions.

4. Finite element model of yarns

Even though the flexible yarn model is more accurate than the persistent contact model, it anyway relies on simplifying assumptions. As a more accurate alternative, albeit at the price of higher computational cost, we have also designed a volumetric FEM model of yarns. The advantage of FEM is that it interpolates the unknown energy function in the continuum and integrates energies from this interpolated function, with accuracy up to the order of shape functions and the integration method. The discrete elastic model previously introduced computes the total energy as the sum of discrete energy terms, with no accuracy guarantees. In the FEM model, we also model yarns as 3D shapes, as shown in figure 1-right, which allow us to study possible deformations at the cross-section. However, this model is computationally more expensive than the previous ones, limiting the number of yarns that can be simulated.

To set up an FEM simulation, we take as input the yarns in their relaxed state from our flexible yarns with contact simulator, creating nodes along the spline in the cross-section and joining them using eight-node hexahedral elements. We use ANSYS LS-DYNA for the simulations, which takes the initial configuration as rest state; therefore, we first define the nodes and elements using straight yarns, and then translate the nodes into their start positions for the simulation.

5. Discussion

The persistent contact model has the potential to become a reference in cloth simulation at the yarn-level, as it achieves good-looking results with a low computational cost. However, yarn-yarn interaction is not handled accurately due to limitations of the model. We have carried out several simulations using the different models documented in the paper, to start evaluating the differences across models. We use Unity to render both the persistent contact and the flexible yarns with contact results, while we use ANSYS LS-DYNA to render results corresponding to FEM simulations.

Figure 2 shows an in-plane fabric load scene and a yarn pull-out scene. The colors in the FEM results correspond to the Von Mises stress visualized in RGB scale; elements in blue have low stress state, while elements in red have high stress state. The in-plane fabric load scene is a good example of contact handling. Yarns get curved while adapting to each other. If there are two perpendicular yarns in contact and one is more stretched than the other, the stretched one will dominate the contact and reduce its curvature, while the other yarn will deform and accommodate to the new configuration. This is well observed both in the flexible yarns with contact model and the FEM model, while the effect is currently not handled by the persistent contact model.

The yarn pull-out scene tries to generate effects that arise naturally which are harder to handle in the persistent contact model. In this example, when a yarn is pulled and the contact between two perpendicular yarns disappears, the persistent crossing node should be deleted, with the consequent recomputation of the degrees of freedom involved. In the flexible yarns with contact model, same as in the FEM model, this example is straightforward as the only difference is that the contact will no longer contribute to the collision energy when it disappears.

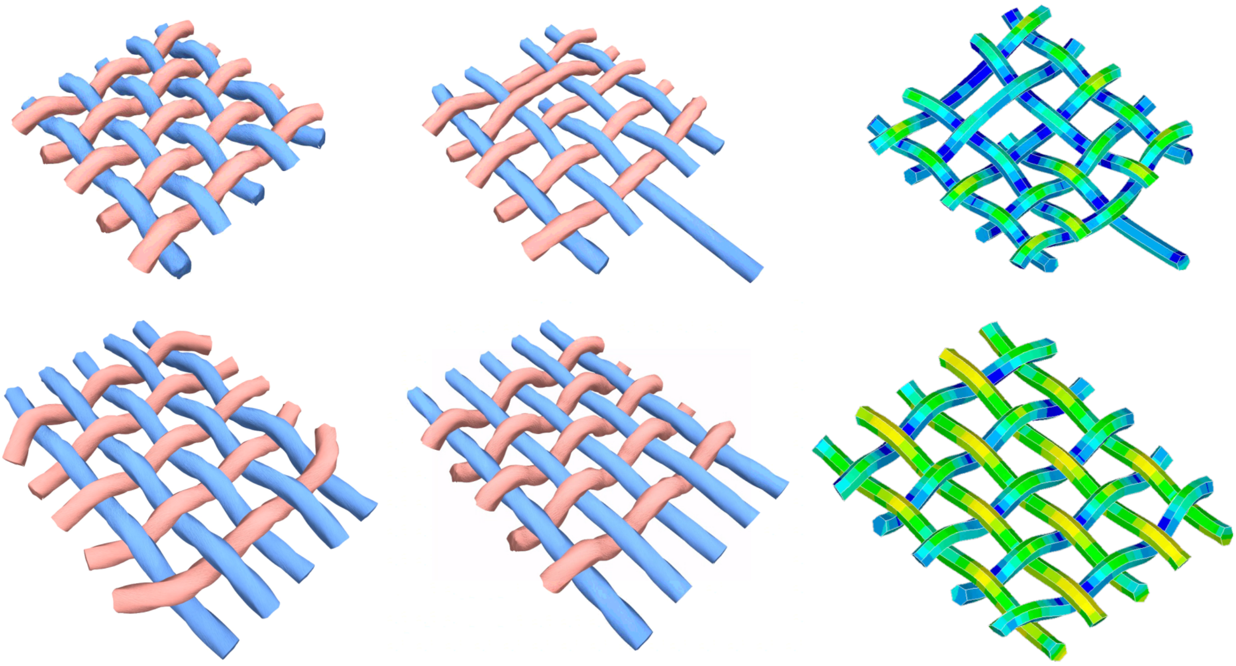

Figure 2: *Results achieved with all three models.* ***Top-left:*** *Woven fabric in its rest state.* ***Top-center:*** *Yarn pulled using flexible yarns with contact.* ***Top-right:*** *Yarn pulled using FEM.* ***Bottom-left:*** *Yarns stretched in one direction using persistent contacts.* ***Bottom-center:*** *Yarns stretched in one direction using flexible yarns with contact.* ***Bottom-right:*** *Yarns stretched in one direction using FEM.*

As the results show limitations of the persistent contact model, in future work we will identify and document the precise differences, and evaluate possibilities for improving the model. We will quantify the geometric non-linearities observed in the models representing yarn contact explicitly and implement them in the persistent contact model. In addition, we will use the complex models to progressively estimate parameters for the persistent contact model.

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