Yarn Level Cloth Simulation

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December 4, 2008
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Papers we will be covering today:

- “Shear buckling and dynamic bending in cloth simulation” (CASA 2008) by Chuan Zhou, Xiaogang Jin, and Charlie C. L. Wang from Zhejiang University, Hangzhou, China
- “Simulating Knitted Cloth at the Yarn Level” (SIGGRAPH 2008) by Jonathan M. Kaldor, Doug L. James, Steve Marschner, Cornell University

Why simulate at a yarn level?

- Most cloth simulations deal in an elastic sheet model
- This yields results which behave similar to leather rather than a woven or knit material
- The yarn-yarn interactions on the micro level are key to getting accurate results on the macro level

Knit vs. woven materials

- Knits
- Non-linear 3-D looping structure
- Consists only of one continuous yarn
- Highly stretchable

- Weaves
- Linear weft and warp structure
- Consists of hundreds of yarns
- Stress causes buckling rather than stretching

Shear buckling and dynamic bending in cloth simulation

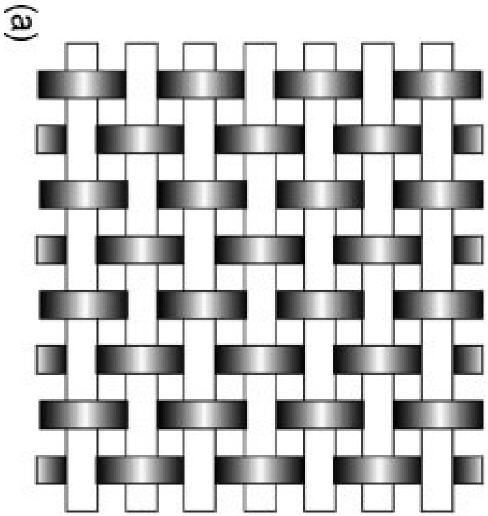
- Structural bending is caused by compressive in-plane deformation
- Shear buckling occurs when the woven material has been stretched to the point where it resists further shearing of the fibers
- Weaves are anisotropic, meaning they have different characteristics during stretching, shearing, and bending

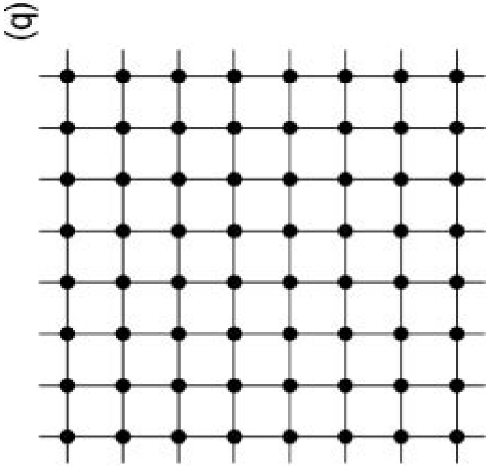
The Contribution

- They have developed a new physical model considering the micro-interweaved structure in woven fabrics with more accurate shear buckling model
- They decouple the buckling deformation into shearing and structural bucklings
- A new dynamic bending model is derived from the thin-shell theory

Shear Buckling on Woven Structure

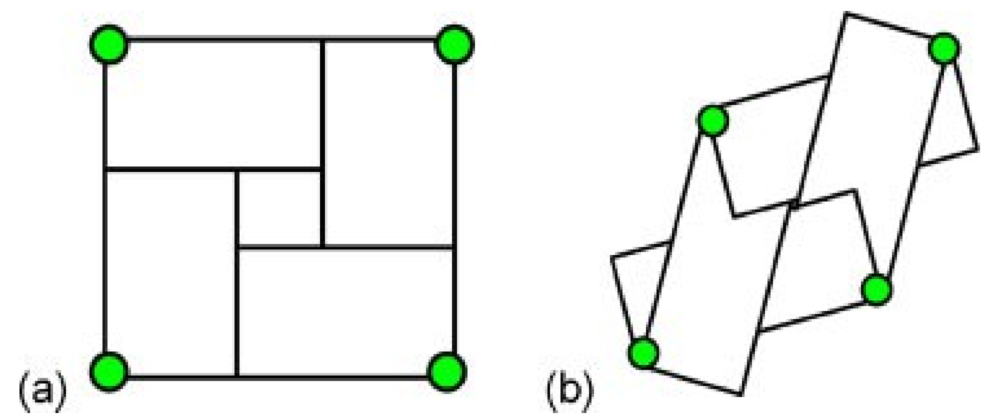
- Shearing stress is related to angle variation between yarns rather than length variation
- Elastic sheet models with simple mass-spring systems can only handle length variations





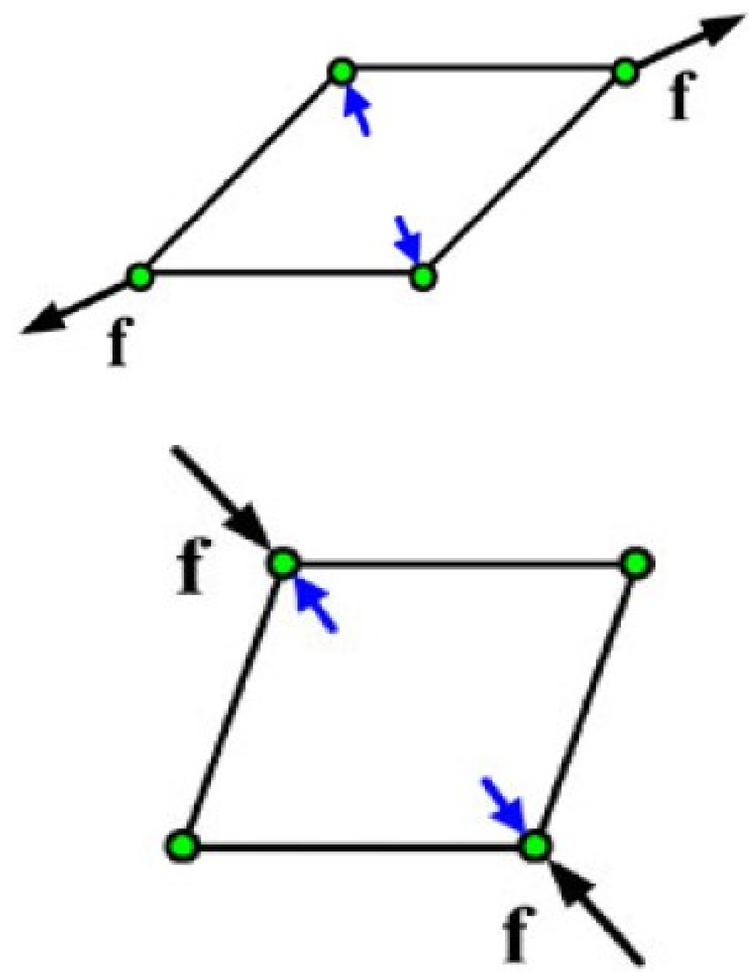
Weft and Warp gaps

- The hole between weft and warp is filled by shearing
- Resistance to further weft/warp rotation under greater stress is what causes the shear buckling



Resistance to compression

- In diagonal stretching the compression forces between yarns are perpendicular to the external load force
- In diagonal compression, the internal forces are opposite the external



Relation between diagonal forces

- α represents the resistance to diagonal extension
- β represents the resistance to diagonal compression

$$\alpha + \beta \equiv 1 \qquad (0 \leq \alpha, \beta \leq 1)$$

- In most cases the stiffness of shearing springs should be much larger than the values of other springs in the system

Dynamic Bending Method

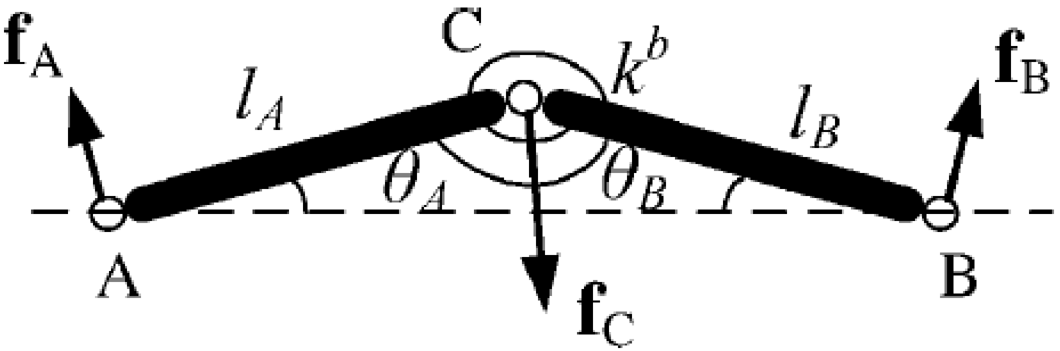
- Linear beam theory model

$$M_x = k^b \kappa = (EI_x)\frac{\mathrm{d}\theta}{\mathrm{d}x}$$

- In the dynamic model, k^b changes depending on the current shape

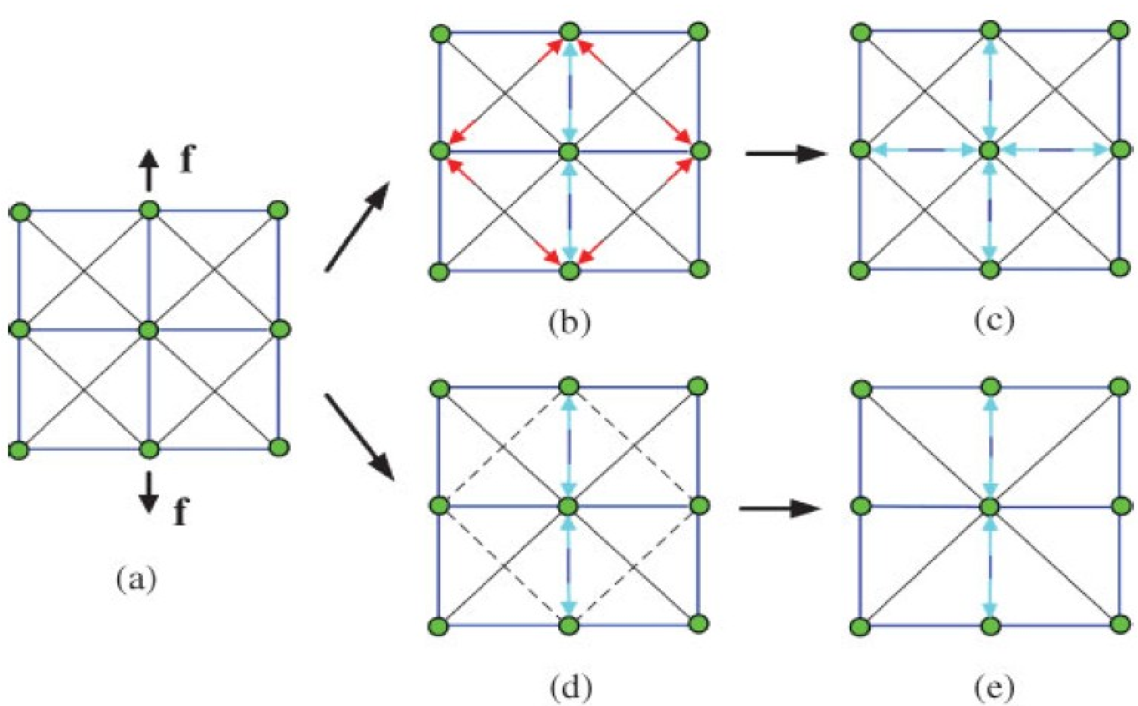
Simplified model with dynamic stiffness

- Bending force: $$\mathbf{f}_A = \frac{\mathbf{e}_A \times \mathbf{M}_C}{l_A}$$
- Where $$\mathbf{M}_C = k^b \frac{\theta_A + \theta_B}{l_A + l_B}\mathbf{n}$$
- From



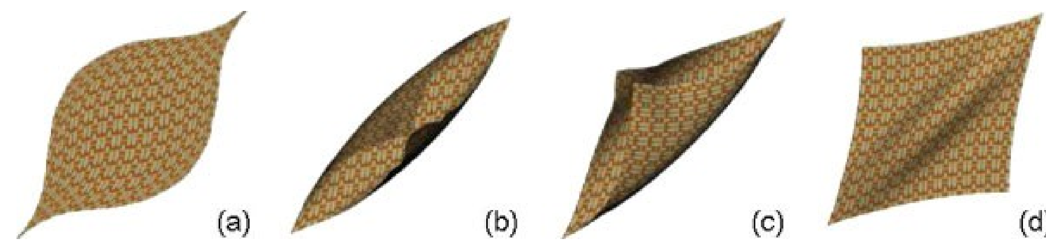
Implementation on a Particle System

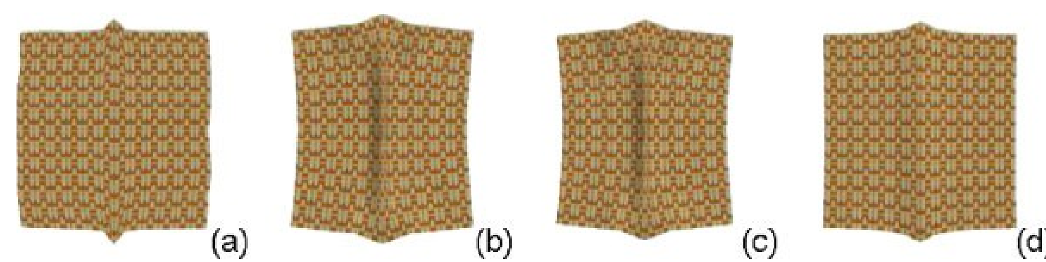
- Shearing springs are only reacted when they are under compression
- Very large stiffness coefficients will be assigned to those compressed shearing springs



Results

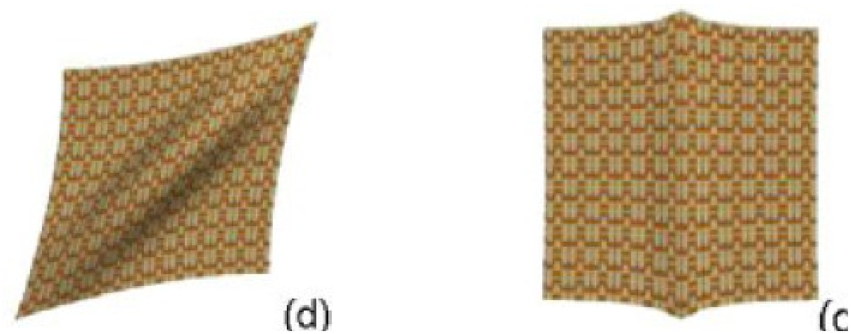
- Two shearing tests:
- One with diagonal shear load at a 45 degree angle from weft and warp
- One with simple stretching along the direction of the yarn





Results

- Their model provides a realistic shear buckling result which is visually similar to real woven materials

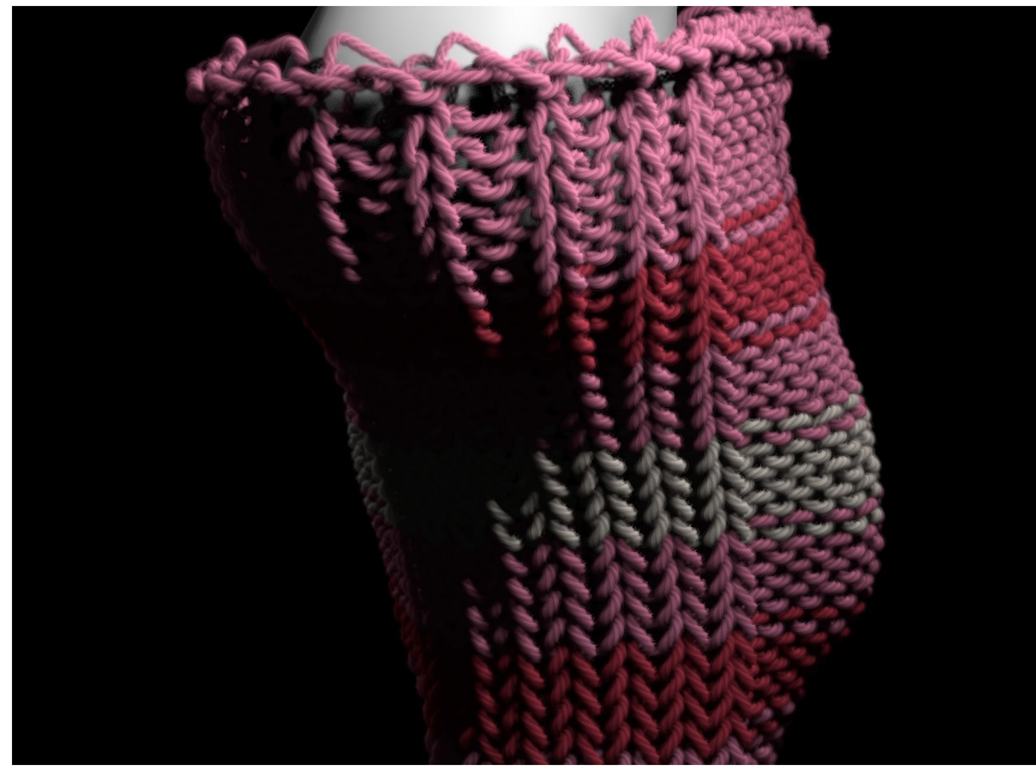


Simulating Knitted Cloth at the Yarn Level

- Few works have focused on knit simulation
- Knits behave very differently from elastic sheet models and even from woven fabrics

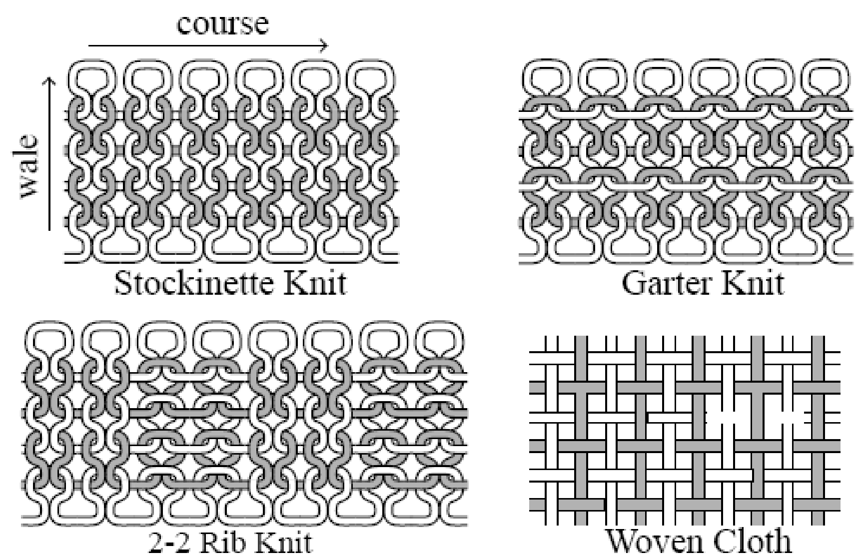
Multiphasic deformations

- There are layers to the deformation of knits materials
- Unrolling of the sheet
- Deformation of woven or knit structure
- Additional load causes the yarns themselves to stretch



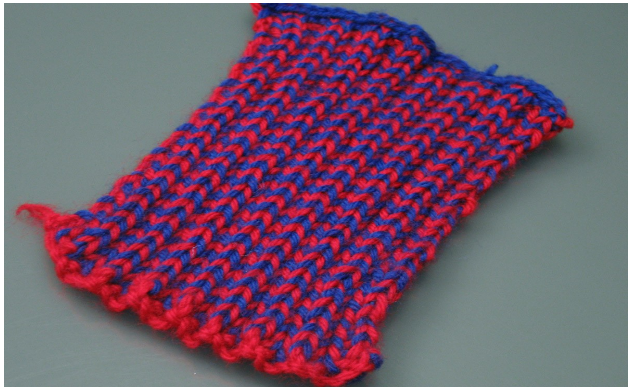
Knit and Purl loops

- The yarn is organized in loops along horizontal rows
- “Knit” stitches come up through the previous loop
- “Purl” stitches come down through the previous loop



Types of knits

- Stockinette – all “knit” stitches
- Garter – alternating “knit” and “purl” stitches
- 2-2 rib – two rows of “knits” followed by two rows of “purls”



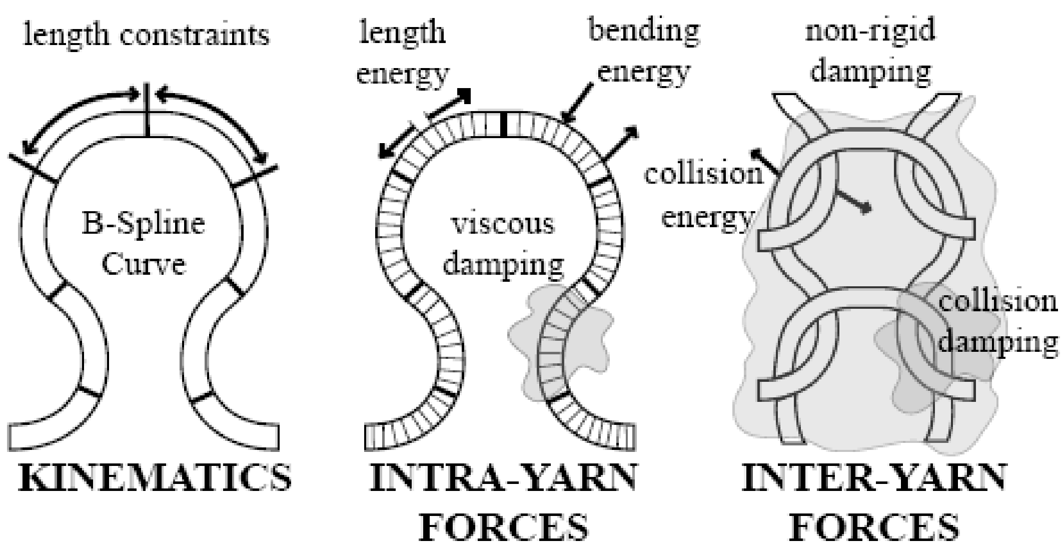
The Yarn-Level Cloth Model

- Yarns are modeled as one continuous open cubic b-spline of radius r
- Indices i, j range over spline segments while k, l range over the control points
- Equation of curve position: $\mathbf{y}(s) = \sum b_k(s)\mathbf{q}_k, \; s \in [0, N]$
- And velocity: $\mathbf{v}(s) = \sum b_k(s)\dot{\mathbf{q}}_k$

Yarn constraints

- Mass:

$$\begin{aligned} \mathbf{M}\,\ddot{\mathbf{q}} &= -\nabla_{\mathbf{q}} E(\mathbf{q}) - \nabla_{\dot{\mathbf{q}}} D(\dot{\mathbf{q}}) + \mathbf{f} \\ \mathbf{C}(\mathbf{q}) &= \mathbf{0}, \end{aligned}$$



Intra-Yarn Properties

- A bending energy function which is quadratic in nature

$$E_i^{\text{bend}} = k_{\text{bend}}\,\ell_i \int_0^1 \kappa_i(s)^2 \, ds,$$

- Inextensibility where the total curve length is a hard constraint but mass can move around

$$C_i^{\text{len}} = 1 - \frac{1}{\ell_i} \int_0^1 \|\mathbf{y}_i'(s)\| \, ds.$$

Yarn-Yarn Collisions

- Yarn collision forces are handled with an energy term:

$$E_{(i,j)}^{\text{contact}} = k_{\text{contact}}\, \ell_i \ell_j \int_0^1 \int_0^1 f\left(\frac{\|\mathbf{y}_j(s') - \mathbf{y}_i(s)\|}{2r}\right) ds\, ds'$$

- Where f(d) is defined as

$$f(d) = \begin{cases} \frac{1}{d^2} + d^2 - 2, & d < 1 \\ 0, & \text{otherwise} \end{cases}$$

Damping and Friction

- Mass-proportional damping:

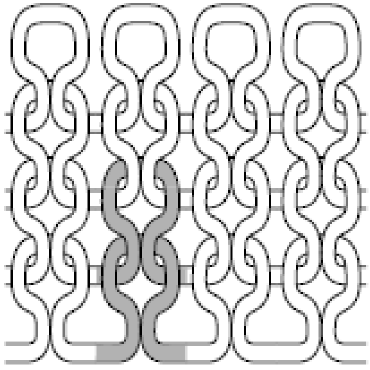
$$D_i^{\text{global}} = k_{\text{global}} \int_0^1 \mathbf{v}_i(s)^T \mathbf{v}_i(s) ds$$

- Contact damping:

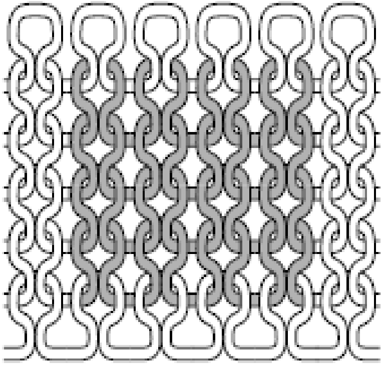
$$\ell_i \ell_j \int_0^1 \int_0^1 \left(k_{dt} \|\Delta \mathbf{v}_{ij}\|^2 - (k_{dt} - k_{dn})(\hat{\mathbf{n}}_{ij}^T \Delta \mathbf{v}_{ij})^2 \right) ds\, ds'$$

- Non-rigid motion damping (fuzz):

$$\frac{\alpha}{r(s)} (\mathbf{v}_{\text{rigid}}(s) - \mathbf{v}(s))$$



Small rigid damping region (repeat every row / column)



Large rigid damping region (repeat every 2 rows / 2 columns)

Additional Constraints

- Gluing the end of the yarn:

$$\mathbf{C}^{\text{glue}} \doteq \mathbf{y}(s_1) - \mathbf{y}(s_2)$$

- Contact with objects of implicit surfaces:

$$\mathbf{E}_i^{\text{obj}} = k_{\text{obj}} \int_0^1 \begin{Bmatrix} (f(\mathbf{y}_i(s)) - f_0)^2, & f(\mathbf{y}_i(s)) < f_0 \\ 0, & \text{otherwise} \end{Bmatrix} ds$$

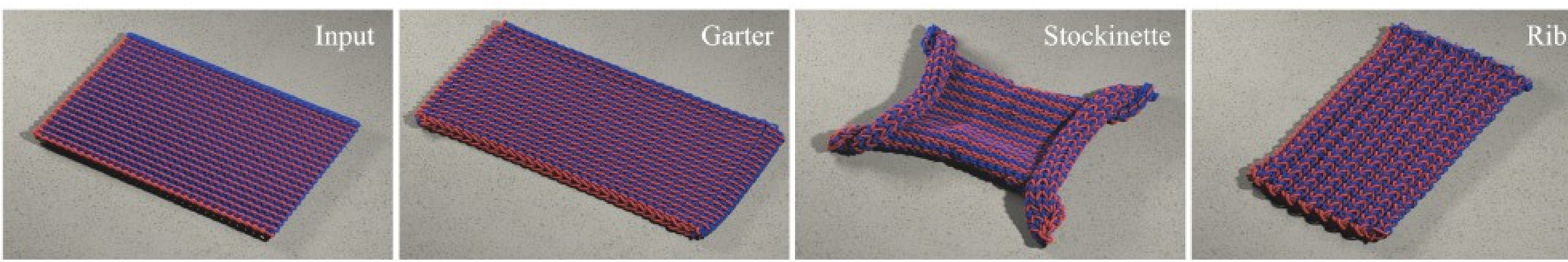
- With distance fields (plane) they employ a velocity filter along with the appropriate frictional impulse

Integrating Yarn Dynamics

- Use an implicit-explicit integration method
- The bottleneck for the integration is usually in the collision detection, so they use spatial culling
- Static bounding spheres limit the collision checking to close neighbors
- AABB tree traversal and contact force evaluation is highly parallelizable

Initial Yarn Configuration

- Input: a knit pattern, spline segments (k per stitch), a set of curves to describe the various kinds of stitches
- Goal: to obtain a properly interconnected configuration which can be relaxed to a rest state



Results

- Code written in Java and run on machines with 4-core Intel Xeon processors at 2.66 GHz
- Rendering time ranged from 4 to 15 mpf
- The model handles constant low-stiffness contact and transient stiff contact between two colliding yarns, but is not as stable in handling constant high-stiffness contact
- Realistic results can be a basis for future approximation models