Techniques for Animating Cloth

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1 Overview (Cansın)

- Motivation
- The Basics
- Types of Cloth
- Properties of Cloth
- Simulation
Motivation

Cloth  We wear it,

Figure: [12]
Motivation

Cloth  We wear it,
       Tables wear it,

Figure:  youtube.com/watch?v=TOTKMvheXI8
Motivation

**Cloth**
We wear it,
Tables wear it,
Even PC’s wear it!
Motivation

**Cloth**

We wear it,
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Non-typical clothes:

- Paper

*Figure: youtube.com/watch?v=ST18eXSjcdQ*
Motivation

**Cloth**

We wear it,
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Non-typical clothes:

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- Skin

*Figure: [9]*
Motivation

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Non-typical clothes :
    • Paper
    • Skin

Figure: [2]
Motivation

Cloth

We wear it,
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Even PC’s wear it!
Non-typical clothes:

- Paper
- Skin
- Flags

Figure: [20]
Motivation

**Cloth**

We wear it,  
Tables wear it,  
Even PC’s wear it!  
Non-typical clothes:

- Paper  
- Skin  
- Flags  
- Curtains - Towels

Figure: [11]
Motivation

Cloth 
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Non-typical clothes:
- Paper
- Skin
- Flags
- Curtains - Towels
- Leaves

Figure: youtube.com/watch?v=dE912X2CkFs
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Simulation A topic of research
since 80’s.

Figure: [12]
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**Simulation**  A topic of research since 80’s.
- *Basically* solved problem
- Some unsolved fine details

*Figure: [12]*
Cloth/Garment  A *flexible* material consisting of a network of *yarns*. 
Techniques for Animating Cloth

Overview

The Basics

Cloth

Cloth/Garment  A *flexible* material consisting of a network of *yarns*.

Yarn  Produced by spinning *wool*, *linen*, *cotton* or other materials.

*Figure:* Wool, linen and cotton
Types of Cloth

- Weaving
- Knitting
- Crochet
- Macrame
- Felt
Weaving

Making *woven* by interlacing yarns at right angles.

**Warp** Yarns that run length-ways of cloth.

**Weft** Yarns that run across from side to side.

*Figure: Warp and weft*
Knitting  Making clothes by loops called stitches pulled through each other.

**Figure:** Stitch schema and actual knit
Techniques for Animating Cloth

Overview

Types of Cloth

Crochet, Macrame, and Felt

Figure: Crochet

Figure: Macrame

Figure: Felt
Techniques for Animating Cloth

Overview

Properties of Cloth

Mechanical Properties of Cloth

Figure: Stretch, shear and bend
Mechanical Properties of Cloth

**Stretch/Compression**  Displacement along warp or weft direction.
- Can’t compress at all.
- Stretched to a limit of 10 percent.

*Figure: Stretch, shear and bend*
Mechanical Properties of Cloth

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**Shear**  Displacement along diagonal directions.

*Figure: Stretch, shear and bend*
Mechanical Properties of Cloth

**Stretch/Compression** Displacement along warp or weft direction.
- Can’t compress at all.
- Stretched to a limit of 10 percent.

**Shear** Displacement along diagonal directions.

**Bend** Curvature of cloth surface.
- Easy to bend.

Figure: Stretch, shear and bend
Visual Properties of Cloth

Figure: Drape and wrinkle
Visual Properties of Cloth

**Drape**  Cloth can be laid onto an object.

*Figure: Drape and wrinkle*
Techniques for Animating Cloth
Overview
Properties of Cloth

Visual Properties of Cloth

**Drape**  Cloth can be layed onto an object.

**Wrinkle**  Cloth has several wrinkles most of the time.

*Figure: Drape and wrinkle*
Simulating Cloth Properties

Hard to simulate because it has,

- Many primitives and/or nodes at model,
- High degree of freedom at those nodes,
- Not perfectly elastic, has stiffness against stretch,
- Variety of properties.
- Collision detection is also hard; same reasons.

Decide between Simple Model vs. Realism.
Simulating Cloth Properties

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Collision detection is also hard; same reasons.
Decide between *Simple Model* vs. *Realism*. 
Physical vs. Non-Physical

- Physical Techniques
- Geometric Techniques
Physical vs. Non-Physical

- Physical Techniques
- Geometric Techniques
Physical vs. Non-Physical

- Physical Techniques - simulate actual behavior
- Geometric Techniques
Physical vs. Non-Physical

- Physical Techniques - simulate actual behavior
- Geometric Techniques - fake it!
2 Traditional Physical Techniques (Cansın)

- Introduction
- Continuum Models - Terzopoulos
- Energy-Based Particle Systems Model - Breen
- Mass-Spring Model - Provot
- Dealing with Time-steps - Baraff and Witkin
- Interactive Animation of Structured Deformable Objects - Barr
Common Structure
Common Structure

**Model**  Mass Points vs. Surface Meshes.
Common Structure

**Model**  Mass Points vs. Surface Meshes.

**Simulation**  Force-based vs. Energy-based.
Common Structure

**Model**  Mass Points vs. Surface Meshes.

**Simulation**  Force-based vs. Energy-based.

**Integration**  Implicit vs. Explicit Integration.
Techniques for Animating Cloth
Traditional Physical Techniques
Continuum Models - Terzopoulos

Model

Figure: Deformable Body Representation

For a point $a$ of deformable body,

Initial Position $\mathbf{r}^0(a) = [r^0_x(a), r^0_y(a), r^0_z(a)]$

Time-varying Position $\mathbf{r}(a, t) = [r_x(a, t), r_y(a, t), r_z(a, t)]$
Techniques for Animating Cloth
Traditional Physical Techniques
Continuum Models - Terzopoulos

Simulation and Integration

Simulate Motion: \[ \mu \frac{\partial r}{\partial t^2} + \gamma \frac{\partial r}{\partial t} + \delta_r \varepsilon(r) = f(r, t) \]

- Position: \( r(a, t) \)
- Mass Density: \( \mu(a) \)
- Energy Density: \( \gamma(a) \)
- Energy: \( \varepsilon(r) \)
- External Force: \( f(r, t) \)
Simulation and Integration

Simulate Motion: \[ \mu \frac{\partial^2 r}{\partial t^2} + \gamma \frac{\partial r}{\partial t} + \delta_r \varepsilon(r) = f(r, t) \]

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Integrate
1. Discretize using finite-element method
2. Numerically integrate using an implicit method
Techniques for Animating Cloth
Traditional Physical Techniques
Continuum Models - Terzopoulos

Results

Figure: A flag, a soft object and a carpet from Terzopoulos’ work
Techniques for Animating Cloth

Traditional Physical Techniques

Energy-Based Particle Systems Model - Breen

Model

Idea

- Friction between *warp* and *weft* is more important than *molecular bonds*
- So *Continuum Model* is not that accurate.
**Model**

**Idea**
- Friction between *warp* and *weft* is more important than *molecular bonds*.
- So *Continuum Model* is not that accurate.

**Model**
- Use *Particle Systems* instead.
- Intersection points of *warps* and *wefts* is the particles.

**Figure:** Particle representation of a woven cloth
Techniques for Animating Cloth

Traditional Physical Techniques

Energy-Based Particle Systems Model - Breen

Simulation and Integration

Simulate

- Energy:

\[ U_i = U_{repel_i} + U_{stretch_i} + U_{shear_i} + U_{bend_i} + U_{gravity_i} \]
Simulation and Integration

- **Simulate**
  - Energy:
    \[ U_i = U_{repel_i} + U_{stretch_i} + U_{shear_i} + U_{bend_i} + U_{gravity_i} \]
  - Use *Kawabata* system to derive \( U_i \).
Techniques for Animating Cloth
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Simulation and Integration

Simulate
- Energy:
  \[ U_i = U_{repel_i} + U_{stretch_i} + U_{shear_i} + U_{bend_i} + U_{gravity_i} \]
- Use Kawabata system to derive \( U_i \).

Integrate
- Let Free Fall
- Minimize energy: *Stochastic Gradient Descent*

Figure: Bending and Shear Plots from Kawabata
Techniques for Animating Cloth

Traditional Physical Techniques

Energy-Based Particle Systems Model - Breen

Results

Figure: Actual vs. simulated cloth drapes from Breen’s work
Techniques for Animating Cloth
Traditional Physical Techniques
Mass-Spring Model - Provot

Model

Idea

- @Terzopolous Cloth is not perfectly elastic. A stiffness property should be added for especially pinned clothes.
- @Breen Static simulation is not enough. Animation should be handled.
Techniques for Animating Cloth

Traditional Physical Techniques

Mass-Spring Model - Provot

Model

Idea

- **@Terzopolous** Cloth is not perfectly elastic. A *stiffness* property should be added for especially pinned clothes.
- **@Breen** Static simulation is not enough. Animation should be handled.

Model

- Use *Particle Systems*.
- Bind particles to each other using *Mass-Spring Model*.

Figure: Structure, shear, and flex springs.
Simulation

Simulate Force: $F_{total} = F_{external} + F_{internal}$
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- $F_{external}$: gravity, wind, drag, etc.
**Techniques for Animating Cloth**

**Traditional Physical Techniques**

**Mass-Spring Model - Provot**

**Simulation**

**Simulate**

Force: $F_{total} = F_{external} + F_{internal}$

- $F_{external}$: gravity, wind, drag, etc.
- $F_{internal}$: $F = k \times x$
Simulation - Internal Forces

- Specify "distance" constraint using flexible spring model...
Specifying "distance" constraint using flexible spring model...

- Structural springs: Sheet-like property
Simulation - Internal Forces

- Specify "distance" constraint using flexible spring model...
  - Structural springs: Sheet-like property
  - Sheer springs: Resist shearing
Techniques for Animating Cloth

Traditional Physical Techniques
Mass-Spring Model - Provot

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- Specify "distance" constraint using flexible spring model...
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  - Bend (flexion) springs: Resist bending
Simulation - Internal Forces

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Integration

Integrate Using basic Euler integration method.

- \(a_{i,j}(t + \delta t) = \frac{1}{m} F_{i,j}(t)\)
- \(v_{i,j}(t + \delta t) = v_{i,j}(t) + \delta t a_{i,j}(t + \delta t)\)
- \(P_{i,j}(t + \delta t) = P_{i,j} + \delta t v_{i,j}(t + \delta t)\)
Techniques for Animating Cloth

Traditional Physical Techniques

Mass-Spring Model - Provot

Post-Processing - Stiffness

**Stiffness**  Force shear and structural springs to not exceed 10 percent.

**Figure:** Without stiffness constraint vs. with stiffness constraint.
The Time-Step Problem

- Large time-steps ⇒ Fast, but unstable
- Small time-steps ⇒ Stable, but slow

**Figure**: With large time-step

**Figure**: With small time-step
Large Steps in Cloth Simulation - Baraff and Witkin

**Idea** Enable large time-steps to speed up simulation.
Large Steps in Cloth Simulation - Baraff and Witkin

Idea  Enable large time-steps to speed up simulation.
Model  Uniform triangular mesh rather than particles.
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Simulation Internal energy functions like in \textit{continuum model}.
Large Steps in Cloth Simulation - Baraff and Witkin

**Idea**  Enable large time-steps to speed up simulation.

**Model**  Uniform triangular mesh rather than particles.

**Simulation**  Internal energy functions like in *continuum model*.

**Integration**  Implicit integration, which generates a matrix solved by *modified conjugated gradient*.
Results

**Figure:** Results of Baraff and Witkin’s work
Overview

Idea

- Baraff and Witkin was so fast, let’s make it real-time.
- Somewhat a hybrid approach.
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Force-based simulation.
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Mass-spring model like *Provot’s.*

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**Integration**
*implicit Euler integration* rather than *explicit.*
Overview

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Mass-spring model like Provot’s.

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Integration
*implicit Euler integration* rather than *explicit*.

Post-processing
Using inverse kinematics, same objective as Provot’s (stiffness).
Results

Figure: Real-time results from Barr’s work
3 Collision Handling (Adil)

- The Problems within Collision Detection and Response
- Internal Dynamics vs. Contact Dynamics
- Proximity Detection and Repulsion Forces
- Robust Collisions
Techniques for Animating Cloth
Collision Handling
The Problems within Collision Detection and Response

Why important?

- A critical part of cloth animation
- A source for simulation errors
- Can be separated from internal dynamics [8, 21]

Proposed approach (Bridson SIGGRAPH Course ’05 [7])

1. Good-looking
2. Robust
3. Fast
Challenges

- Cloth is thin.
Techniques for Animating Cloth
Collision Handling
The Problems within Collision Detection and Response

Challanges

- Cloth is thin.
- Penetration is very visible, hard to recover back after.
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  ...and all primitives are in the surface!
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- Large number of collisions, with different characteristics
- Handling self-intersections
- Handling intersection with other structures
- Handling elastic collisions and frictions
Techniques for Animating Cloth
Collision Handling
Internal Dynamics vs. Contact Dynamics

Idea: Separate internal dynamics

First simulate internal dynamics, than try to recover from contacts
Idea: Separate internal dynamics

First simulate internal dynamics, than try to recover from contacts

- Integrate state at $t_n$ to $\text{tappr}x_{n+1}$ using internal forces only
- "Solve the collisions" in $\text{tappr}x_{n+1}$, get a non-penetrating state $t_{n+1}$
- Update particle velocities to approach $t_{n+1}$
  - $dv = (x_{n+1} - x_n)/dt$ or use damping dynamics
Idea: Separate internal dynamics

First simulate internal dynamics, than try to recover from contacts

- Integrate state at $t_n$ to $t_{apprx}x_{n+1}$ using internal forces only
- "Solve the collisions" in $t_{apprx}x_{n+1}$, get a non-penetrating state $t_{n+1}$
- Update particle velocities to approach $t_{n+1}$
  - $dv = (x_{n+1} - x_n)/dt$ or use damping dynamics

Question: How to "Solve the collisions"?
Proximity detection and Repulsion Forces

Detect close parts, apply repulsion to separate them
Techniques for Animating Cloth
Collision Handling
Proximity Detection and Repulsion Forces

Proximity detection and Repulsion Forces

Detect close parts, apply repulsion to separate them

Particles $\rightarrow$ Triangulation $\rightarrow$ Barycentric coordinates of close points.

Two valid common "closest" configurations
- Point - Triangle
- Edge - Edge
Techniques for Animating Cloth
Collision Handling
Proximity Detection and Repulsion Forces

Proximity: Only A Lot Faster

Bounding Volumes (Collision culling)
- Introduce bounding volumes for triangles
- Organize BVs / build a hierarchy
Applying Repulsion

- Find direction of repulsion
Applying Repulsion

- Find direction of repulsion
- Choose your repulsion approach
  - Damped spring between closest points
  - Kinematic solutions
Applying Repulsion

- Find direction of repulsion
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- Distribute repulsion from point to triangle corners
  - Barycentric coordinates put into good use
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- Find direction of repulsion
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- Distribute repulsion from point to triangle corners
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- Calculate the impulse on particles
- Friction? A problem on its own! Yet, simple models are available
  - Ex: Coulomb’s model (for static and kinetic friction)
Questions? And problems...

- Does not guarantee no inter-penetration
- Stiff (expensive) vs non-stiff repulsion forces/springs?
- Applying large repulsion forces as a precaution ⇒ floating behaviour without friction
Dealing with Robustness Problem

Identify problems, propose solutions
Dealing with Robustness Problem

- Identify problems, propose solutions

- Respond to fast velocities ⇒ Identify not the intersection at timestep, but the exact time and position.
- Handle floting point errors (in which side you are on the cloth?)
- Avoiding tangling [4]
Given current non-intersecting position and velocity, compute next position

Find if any intersection (using same pair types as above) occurred in this timeline.

- Need volumetric and time-parametrised approach.
- Not easy: Reduced from 5th order poly to cubic. [21]

Assume: Constant velocity during timestep
After collision update, new positions are found...
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Q: What if these new positions result in "new" collisions?
A: Iterate collisions again (by first finding potential pairs...)
After collision update, new positions are found...

- Q: What if these new positions result in ”new” collisions?
- A: Iterate collisions again (by first finding potential pairs...)

Solve using inelastic collisions and similar repulsion-based logic
Impact zones

Idea: Self-colliding cloth is restricted in relative motion.
Impact zones

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Impact Zones are:

- Initially per vertex zones
- Merged into bigger rigid zones using colliding smaller zones
- Provides more global resolutions
Impact zones

Idea: Self-colliding cloth is restricted in relative motion.

Impact Zones are:
- Initially per vertex zones
- Merged into bigger rigid zones using colliding smaller zones
- Provides more global resolutions

Carefully manage rigid impact zones:
- Need to conserve total linear and angular momentum of the zone during integrations.
- They should be short-lived and small [8]
Proposed collision pipeline [7]

1. Repulsions: Follow the basics
2. Geometric collisions: Handling high velocity penetrations
3. Impact zones: Improved stability of iteration relaxations
Proposed collision pipeline [7]

1. Repulsions: Follow the basics
2. Geometric collisions: Handling high velocity penetrations
3. Impact zones: Improved stability of iteration relaxations
Remaining problems:

- Detecting collisions using history-based approach is error-prone.
- An error results in cloth tangling
Untangling Solution [4]

The solutions is composed of two methods:

- Flypapeering: A collision detection method that can deal with pinching.
Untangling Solution [4]

The solutions is composed of two methods:

- **Flypapering**: A collision detection method that can deal with pinching.
- **GIS**: Global intersection analysis which can recover tangles.
  - Works even on tangled (intersecting) initial condition (since not history based).
  - Sometimes applies attraction forces rather than repulsion!
Techniques for Animating Cloth
Collision Handling
Robust Collisions

"The girl Boo is happy, with her cloth tangle free."
Monsters Inc. [4]
Techniques for Animating Cloth
Geometric Techniques
Cloth without Cloth

4 Geometric Techniques (Adil)
- Cloth without Cloth
- Wrinkling Coarse Meshes on the GPU
Let’s take it easy:
Try to solve the wrinkles around skeleton joints “visually”.
Techniques for Animating Cloth
Geometric Techniques
Cloth without Cloth

Cloth without Cloth

The ingredients

- A static normal map for "unfolded" surface.
- A static normal map for "folded" surface.
- A bend map
Techniques for Animating Cloth

Geometric Techniques

Cloth without Cloth

**Cloth without Cloth**

### Cooking for animation

- Get the joint angle.
- Transform it into a blending coefficient.
- Blend unfolded and folded texture.

### The Meal

An animation of a fold-like structure appearing.

Demo
**Evaluation**

<table>
<thead>
<tr>
<th>Con's</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Aimed for skeletons</td>
</tr>
<tr>
<td>- Assumes that the cloth is tightly wrapped</td>
</tr>
<tr>
<td>- Not scalable, limited in cloth behaviour</td>
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<td>- And requires uniform uv coordinates</td>
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Evaluation

**Con’s**
- Aimed for skeletons
- Assumes that the cloth is tightly wrapped
- Not scalable, limited in cloth behaviour
- And requires uniform uv coordinates

**Pro’s**
- Gain significant speed when folding pattern doesn’t need to be high fidelity
Extentions [22]

Figure 4. Proposal to areas of influence setup.

Figure 9. Left and right eyebrow.
Wrinkling Coarse Meshes on the GPU [16]: Results

Figure: Varius deformed cloth models, as shown in [16]
Another (more complex) geometric model, not physically dynamic

- Works an animated models with mesh deformations (Bones/morphing/physical sim)
- Can maintain global consistency
- Shading using bump mapping / parallax mapping (for low tessellation)
- Can specify wrinkle wavelength - height profile (sinusoidal / accordion)
Method basics

Preparation:
- Remove copies of vertices with same positions but different uv’s
- Result: A vertex adjacency pseudo-texture
Method basics

Deformation:

- **Skin**: Blending vertices with multiple influences (matrix palette skinning)
- **Crush**: Pre and post tangent spaces ⇒ Cloth compression data (Direction and amplitude per vertex)
- **Wrinkle Field**: Represented by a plane wave, but the phase factor is missing
  - Randomize the phase, then apply regression

Rendering

- **Lighting**: Computation of normals along the wave...
- **Texturing**: Deforming texture coordinates to follow the wave (Parallax Mapping)
Parallel Techniques (Adil)
TO-DO: Apply X operation to every cloth particle.

Possible Candidates:
- Dynamics: Force accumulation and integration
- Collision detection
Outline

1. For every particle, apply forces (One pass)
2. In each relaxation step, for every particle
   1. Evaluate the spring constraints (Multiple passes)
   2. For every intersectable geom, check for collision (One pass)
Techniques for Animating Cloth
Parallel Techniques (Adil)

Outline

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Use Verlet Integration \([25]\):
\[ P(t + 1) = P(t) + k(P(t) - P(t - 1)) + \Delta t^2 F(t) \]
GPU Simulation: Dynamics

Particle positions and normals $\Rightarrow$ \textit{GPUfloatingpointtextures}

\textbf{Figure:} Performing the integration, for each global spring type [16]

Note: To simulate structural (4) and shear (4) springs: 4+4 passes used.
Harnessing new features of GPU’s [25]

- Store particles in buffer, not texture
  - Render to buffer, not texture
  - Process in geometry and vertex shaders, not pixel shader
- Single geometry shader call:
  - Up to 6 spring distance constraints (using triangle adjacency input)
- Single vertex shader call:
  - Must evaluate independent constraint groups in parallel.
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