Porous Deformable Shell Simulation with Surface Water Flow and Saturation

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Motivation

• Fluids
  – Small scale
  – Large scale

• Objects
  – Rigid
  – Deformable

• Interaction
  – Waterproof?
Related Work

- Lenaerts *et al.*
  - 2008, SIGGRAPH, Porous flow in particle-based fluid simulations

- Huber *et al.*
  - 2011, CGI, Wet cloth simulation

- Patkar and Chaudhuri
  - 2013, TVCG, Wetting of porous solids
Two-Layer Model

- Surface layer
- Interior layer
Surface Flow

- Fluid simulation in 2D (texture space) with the variational approach [Mullen et al.]

- External forces
  - Projected onto the 2D domain

\[
\begin{bmatrix}
  f_T \\
  f_B
\end{bmatrix} =
\begin{bmatrix}
  \vec{T} \cdot \vec{f} \\
  \vec{B} \cdot \vec{f}
\end{bmatrix}
\]
Capillary Flow

- Absorption: surface → interior

\[
\Delta m_{(i,j)} = \rho_w H_{(i,j)} \varepsilon \left( \frac{\sigma \psi \cos \Phi}{\eta d_c} \right)^{\frac{1}{2}} A \Delta t^2
\]

\[
H_{(i,j)} = \begin{cases} 
1 & \rho_{(i,j)} \cdot (1 - S_{(i,j)}) > 0 \\
0 & \text{otherwise}
\end{cases}
\]

\[
\rho_{(i,j)}: \text{mass density computed through surface flow simulation}
\]

\[
S_{(i,j)}: \text{saturation degree}
\]

\[
\rho_w: \text{constant water density}
\]

\[
\varepsilon: \text{porosity}
\]

\[
\sigma: \text{surface tension}
\]

\[
\psi: \text{permeability}
\]

\[
\Phi: \text{contact angle}
\]

\[
\eta: \text{dynamic viscosity}
\]

\[
d_c: \text{effective pore radius}
\]

\[
A: \text{contact area}
\]
• In a cell \((i,j)\)
  – Volume of cell
    • \(V\)
  – Mass contained at cell \((i,j)\) of the surface layer
    • \(m^s_{(i,j)} = \rho_w \rho_{(i,j)} V\)
  – Capacity of mass at cell \((i,j)\) of the interior layer
    • \(m^i_{(i,j)} = \epsilon \rho_w (1 - S_{(i,j)}) V\)

\[
\Delta m'_{(i,j)} = \min(m^s_{(i,j)}, m^i_{(i,j)}, \Delta m_{(i,j)})
\]
Capillary Flow (cont’d)

• Different permeabilities

Low permeability vs. High permeability
Capillary Flow (cont’d)

- Mass change
  - Surface layer: cyan
  - Interior layer: magenta
  - High-permeability: dotted
  - Low-permeability: solid
Capillary Flow (cont’d)

• Diffusion: interior

\[
\frac{\partial S}{\partial t} = \nabla \cdot (D \nabla S)
\]

\[
D(\epsilon_l) = \frac{3\sigma \cos \Phi \sin^2 \beta \, d_c \epsilon_l}{20\eta \epsilon}
\]

\( \epsilon_l \): fraction of the cell volume occupied by water

\( \beta \): average angle between the capillaries and the surface of the object

– Solve numerically...
Capillary Flow (cont’d)

- Reference to the state variables
  - Mass density: $\rho_{(i,j)}$
  - Saturation degree: $S_{(i,j)}$
Changes in Material Properties

- Mass: porous material + water

\[ M_{(i,j)} = (\rho_o (1 - \epsilon) + \rho_w \epsilon S_{(i,j)} + \rho_{(i,j)}) V \]

- \( \rho_o \): density of the porous material
- \( V \): volume of a cell

- Stiffness
  - Stretching
  - Bending

\[ k'_s = (k_{min} - k_s) \sqrt{S_e} + k_s \]
Changes in Material Properties (cont’d)

- Effects of changes in mass and stiffness
Changes in Material Properties (cont’d)

- Tearing
  - Stretch ratio limit: $\varepsilon$

$$
\varepsilon' = \max(\varepsilon - \alpha (S_e)^\gamma, \varepsilon_{\text{min}})
$$
Changes in Material Properties (cont’d)

- Discontinuity after tearing

Neumann boundary condition for surface and capillary flows
Changes in Material Properties (cont’d)

• Comparison of tearing effects
Experiment

- **System**
  - Intel Core i5-2500K 3.30GHz CPU
  - 8GB memory

- **Fluid**
  - CFL: 1
  - 512 x 512

- **Deformable shells**
  - 4K vertices and 8K polygons

- **Simulation time**
  - 3~4 sec./frame
Conclusion and Future Work

• Simulation
  – Dynamics of deformable shells (with PBD)
  – Surface water flow
  – Capillary flow involving absorption and diffusion of water

• Future work
  – Various full 3D effects: squeezing, sinking, dissolving, evaporation, condensation, etc.
Q/A

Thank you