15-464/15-664 Reference List for April 1, 2020

The theme for today was simulation of deformable bodies. We looked at Shape Matching, As-Rigid-As-Possible, and Finite Element techniques.

Shape Matching

We started today by looking at the use of Shape Matching for fast, stable, deformable body simulation.

Müller, Matthias, Bruno Heidelberger, Matthias Teschner, and Markus Gross. "Meshless deformations based on shape matching." *ACM transactions on graphics (TOG)* 24, no. 3 (2005): 471-478.
https://dl.acm.org/doi/abs/10.1145/1073204.1073216
https://www.youtube.com/watch?v=LAoQJ1dhk1w

As-Rigid-As-Possible

We followed up with an exploration of the As-Rigid-As-Possible technique for animation. The three papers below cover the 2D, 3D, and 3D with simulation versions of this approach:

Igarashi, Takeo, Tomer Moscovich, and John F. Hughes. "As-rigid-as-possible shape manipulation." *ACM transactions on Graphics (TOG)* 24, no. 3 (2005): 1134-1141.
https://www-ui.is.s.u-tokyo.ac.jp/~takeo/research/rigid/index.html

Sorkine, Olga, and Marc Alexa. "As-rigid-as-possible surface modeling." In *Symposium on Geometry processing*, vol. 4, pp. 109-116. 2007.
https://igl.ethz.ch/projects/ARAP/

Choi, Min Gyu, and Jehee Lee. "As-rigid-as-possible solid simulation with oriented particles." *Computers & Graphics* 70 (2018): 1-7.
https://www.sciencedirect.com/science/article/abs/pii/S0097849317301206
https://www.youtube.com/watch?v=Ja1MSoMRKgs

Finite Element

We then took a look at the finite element method, with reference to this paper. Whiteboard notes are attached below. You can find the video from the link that follows the paper reference.

O'Brien, James F., and Jessica K. Hodgins. "Graphical modeling and animation of brittle fracture." In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, pp. 137-146. ACM Press/Addison-Wesley Publishing Co., 1999. http://graphics.berkeley.edu/papers/Obrien-GMA-1999-08/index.html

The following paper discusses how to make the approach robust to large deformations, including element inversion:

Irving, Geoffrey, Joseph Teran, and Ron Fedkiw. "Invertible finite elements for robust simulation of large deformation." In *Proceedings of the 2004 ACM SIGGRAPH/Eurographics symposium on Computer animation*, pp. 131-140. Eurographics Association, 2004. http://dl.acm.org/citation.cfm?id=1028541

The basic finite element technique discussed in these papers was extended to simulate goop. We couldn't play this video in class, but you can find it at the link below.

Goktekin TG, Bargteil AW, O'Brien JF. A method for animating viscoelastic fluids. InACM Transactions on Graphics (TOG) 2004 Aug 8 (Vol. 23, No. 3, pp. 463-468). ACM. http://graphics.berkeley.edu/papers/Goktekin-AMF-2004-08/

A question came up as to whether this approach is embarrassingly parallel. The answer would appear to be yes, but it is not as simple as it first appears. This paper contains an in-depth discussion of the issues we encountered.

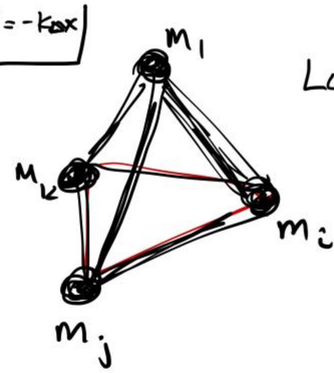
Kim J, Pollard NS. Fast simulation of skeleton-driven deformable body characters. ACM Transactions on Graphics (TOG). 2011 Oct 1;30(5):121. http://www.cs.cmu.edu/~junggon/projects/fastsimuldbody/fastsimuldbody.htm

We had time to have a quick look at one recent research paper on identifying simulation parameters for such simulations from observed motion. The paper is here:

Hahn, David, Pol Banzet, James M. Bern, and Stelian Coros. "Real2Sim: Visco-elastic parameter estimation from dynamic motion." *ACM Transactions on Graphics (TOG)* 38, no. 6 (2019): 1-13. https://dl.acm.org/doi/abs/10.1145/3355089.3356548
https://www.youtube.com/watch?v=oYsKl2E4b1U&feature=youtu.be

FINITE ELEMENT SIMULATION

$f = -k\Delta x$



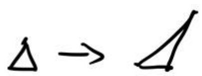
Lumped mass model

(1) Compute **Strain** (deformation)

Green's strain tensor ϵ

3x3 Matrix

Strain rate tensor ν



(2) Compute **Stress** (internal force)

3x3 matrix (tensor) $\sigma^{(\epsilon)}$

elastic stress due to strain $\sigma^{(\epsilon)}$

viscous stress due to strain rate $\sigma^{(\nu)}$

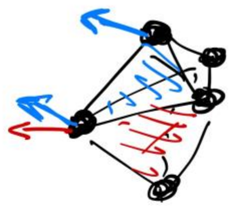
Simplifying assumption — isotropic material

4 parameters that determine behavior

μ - rigidity λ - resist Δvolume

ϕ, ψ - how quickly dissipates kinetic energy

(3) Compute node forces from stress



(4) Update node state from forces