Real-time Cloth Simulation Using Projective Dynamics

I've implemented a real-time cloth solver using projective dynamics[1] and discrete quadratic bending energy[2]. User can drag the cloth via custom handle and play around with different simulation parameters. Collision is not implemented since proper cloth self collision is *really* hard and I just run out of time.

Compile From Source

To compile the project from source, you need to install `cmake` and a cmake generator like `make` or `ninja`.

In addition, make sure your compiler of choice support C++20. Please refer to the table below.

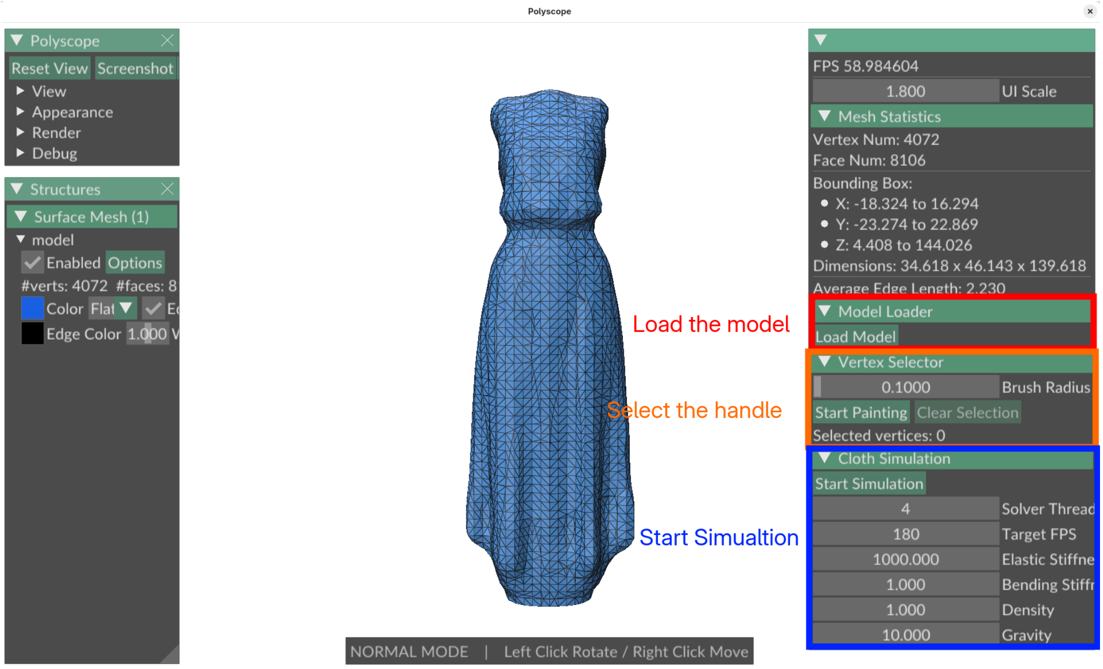
compiler	recommend version
gcc	>= 12
clang	>= 12
msvc	>= 19.29

To compile, go the the root directory,

```
cmake --preset Release
cmake --build build/release
# limit the job num if you run out of memory
cmake --build build/release -j 2
```

That's it! The binary is located at `build/release/main`.

Usage Guide



#verts: 4072 #faces: 8

Edge Color 1.000

FPS 58.984604

1.800 UI Scale

Vertex Num: 4072
Face Num: 8106
Bounding Box:
- X: -18.324 to 16.294
- Y: -23.274 to 22.869
- Z: 4.408 to 144.026

Dimensions: 34.618 x 46.143 x 139.618
Average Edge Length: 2.230

0.1000 Brush Radius

Selected vertices: 0

4 Solver Thread
180 Target FPS
1000.000 Elastic Stiffne
1.000 Bending Stiffr
1.000 Density
10.000 Gravity

NORMAL MODE | Left Click Rotate / Right Click Move

Load the model

Select the handle

Start Simualtion

1 Getting Started

1. **Launch the Application:** Run the compiled executable directly. Optionally, you can pass in the path of a model file as cli arg.
2. **Load a Mesh:** Click the "Load Model" button in the Load Mesh panel.

I've provided some default model in the `data` directory.

2 Paint The Handle

To create a handle that can be used later in cloth simulation, you need to use paint mode to select vertices.

Click the "Start Painting" button to enter paint mode. In paint mode, **left click to paint** and **right click to erase**. When you are finished, click the "Stop Painting" button.

3 Cloth Simulation

After adjusting simulation parameters, click the "Start Simulation" button to enter simulation mode. In simulation mode, you can drag the handle by **holding Control + left clicking**.

Below are a quick table for all simulation parameters.

Parameter	Description	Recommend Value
Solver Thread	Number of thread the solver will use. Since the app is cache bound, setting it too high will degrade the performance.	4 - 8
Target FPS	The internal fps of solver. High stiffness requires high fps.	180 - 540
Elastic Stiffness	The membrane stiffness of the cloth. You typically want this to be super high.	1000 - 10000
Bending Stiffness	The bending stiffness of the cloth.	0.01 - 10
Density	The density of the cloth.	0.1 - 1
Gravity	The gravitational acceleration.	10 - 50

Technical Detail

Theoretical Background - Journey to Projective dynamics

Initially, I intended to adopt position-based techniques such as XPBD. However, during my research, I came across the paper *Discrete Quadratic Curvature Energies*, which demonstrated that bending energy can be effectively approximated using a bi-Laplacian term[1].

This makes me wonder. **Wait a moment... Can I somehow simplify elastic energy to quadratic from so the system can be solved in one step?**

This motivated me to explore alternative real-time method which eventually led to **Projective Dynamics**[2]. The gist of it is that if the distance form the current configuration to the rest configuration is small enough, we can approximate any complex energy as quadratic. Combining this with quadratic bending energy, the whole system energy becomes quadratic. This is the method SOTA cloth model use.

The simulation pipeline becomes:

1. Solving projection (closest rest configuration) locally. Trivially parallelized.
2. Solving global system via a single sparse linear solve.

Software Stack

Numerical

- `libigl`
- `eigen`

UI

- `polyscope`
- `portable-file-dialogs`

Others

- `spdlog`
- `openmp`

What is missing and what I've learned

Solving the cloth physics itself is just a small part of the story. Apart from the cloth model itself, there's damping, friction, and **collision**. Oh god, resolving cloth self collision is ***difficult***. To resolve collision accurately while maintaining some level of performance, SOTA method[3] [4] [5] often

- use some sort of level-of-detail algorithm to reduce geometry
- space partitioning/hashing algorithm to query potential collision
- continuous collision detection
- contact force resolution
- all of above with GPU parallelization

In a nutshell, cloth simulation is an active and difficult research field in computer graphics. Even just aiming for visually convincing simulation requires multiple complex algorithm and huge engineering effort.

Despite only implementing a small part of the simulation pipeline, I’ve learned a lot about physical simulation, numerical methods, and optimization techniques. After this project, I've obtained a rough view of the cloth and physics based simulation landscape. And I now really appreciate those "natural looking" simulations.

Thank you

I would like to sincerely thank Professor Daniele and all the TAs for this outstanding course. It is exceptionally well-designed, featuring interactive demos and a well-structured curriculum that introduces many fundamental concepts and algorithms in computer graphics. After completing this course, I had a much easier time reading graphics papers, thanks to the solid foundation.

1. S. Bouaziz, S. Martin, T. Liu, L. Kavan, and M. Pauly, “Projective dynamics: fusing constraint projections for fast simulation,” *ACM Trans. Graph.*, vol. 33, no. 4, p. 154:1-154:11, Jul. 2014, doi: 10.1145/2601097.2601116. ↩ ↩

2. M. Wardetzky, M. Bergou, D. Harmon, D. Zorin, and E. Grinspun, “Discrete quadratic curvature energies,” *Computer Aided Geometric Design*, vol. 24, no. 8, pp. 499–518, Nov. 2007, doi: 10.1016/j.cagd.2007.07.006. ↩ ↩

3. M. Tang, tongtong wang, Z. Liu, R. Tong, and D. Manocha, “I-cloth: incremental collision handling for GPU-based interactive cloth simulation,” *ACM Trans. Graph.*, vol. 37, no. 6, p. 204:1-204:10, Dec. 2018, doi: 10.1145/3272127.3275005. ↩

4. R. Bridson, R. Fedkiw, and J. Anderson, “Robust treatment of collisions, contact and friction for cloth animation,” *ACM Trans. Graph.*, vol. 21, no. 3, pp. 594–603, Jul. 2002, doi: 10.1145/566654.566623. ↩

5. X. Li *et al.*, “Subspace-Preconditioned GPU Projective Dynamics with Contact for Cloth Simulation,” in *SIGGRAPH Asia 2023 Conference Papers*, in SA ’23. New York, NY, USA: Association for Computing Machinery, Dec. 2023, pp. 1–12. doi: 10.1145/3610548.3618157. ↩