Cloth Dynamics Affected by Fluid

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Abstract

In this paper, we present implementation details regarding the effect that fluid has upon cloth when passing through it, using the work of [Guendelman et al 2005]. We build upon our previous fluid and cloth simulations by coupling the fluid and the cloth such that the cloth moves with the fluid. Our work assumes that the cloth is completely permeable, and thus does not impact the flow of the fluid. Examples will show that our system accurately depicts the flow of cloth given the premise that the fluid is unaffected by the presence of the cloth.

CR Categories: I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Physically based modeling;

Keywords: fluid, cloth

1 Introduction

One common problem in fluid simulation is allowing the fluid to interact with other objects, especially cloth. This is partially due to the differences in implementation; fluids use Eulerian simulation, while cloth uses Lagrangian methods. We want to simulate this interaction because both cloth and fluid are very hard to hand animate because of their large degrees of motion. Fluid and solid coupling has been a subject of study for a long time, but cloth is too thin to be properly effected by the fluid in this system.

We use [Guendelman et al 2005]'s solution to this problem to create reasonable simulations of fluid and air interacting with cloth. Unlike Guendelman, we are primarily concerned with one-way coupling. This of course means that our simulation is less accurate, because we do not account for how the fluid flow changes. Similarly, we do not model the air as a fluid, but instead maintain constant pressure outside of the fluid. These constraints were chosen in order to develop a strong starting position that is easily expandable.

2 Prior Work

Fluid simulation was described by [Foster and Metaxas 1996] as a system of Navier-Stokes equations. [Guendelman et al 2005] further improved the system by deriving equations to allow for coupling cloth and fluid dynamics. Two way coupling was first discussed in [Noh 1964].

We also made extensive work of [Provot 1995] in developing our cloth simulation.

3 The Cloth Simulation

We simulate our cloth with a mass-spring system as described in [Provot 1995]. We chose this system to simulate our cloth because it allows for us to put large stresses on our cloth without causing the cloth to deform or the simulation to break; this proved crucial for our application, as the fluid causes large stretching and bulging.

This model works by using a grid of springs; each vertex has springs attached to its immediate neighbors, its diagonal neighbors, and its once removed neighbors, to simulate structural, shear, and bend forces respectively. To move a point, we apply the force of gravity, all spring forces acting on the point, and the force applied by the movement of the surrounding medium to calculate it acceleration, which is used to calculate the velocity, which is then used to calculate the new position; the point is then moved. With large time steps, the cloth behaves erratically; this is because the initial acceleration from gravity is high, which causes the cloth to stretch, which causes another large acceleration; the cycle continues, and the cloth 'explodes'.

Specifically, we used the following equations:

- $F = -kX$
- $F = ma$
- $v_{i+1} = v_i + a_i * dt$
- $x_{i+1} = x_i + v_i * dt$

3.1 Provot Correction

Another measure taken to prevent the explosion of cloth is Provot correction used on the structural and shear springs. Provot correction takes effect when our springs are over-stretched or over-compressed; when a spring meets one of these extreme conditions, we simply change the points on either end such that the spring is now on the boundary of this extreme condition. This allows our cloth to react well to the fluid, but prevents other extreme responses, such as fabric tearing, that we decided not to implement. Our algorithm for Provot correction checks that the spring is not over stretched; if it is, then we check if either point is fixed. If one point is fixed, we move the second point to the point that is the maximum distance from the fixed point in the direction from the fixed point to the other; if neither are fixed, we move each point half of the maximum distance from the center of the line segment. We then repeat this process 3 times, to allow any issues caused by the corrections to settle. We perform this correction every frame, adding an operation of O(n) to our calculations, which hurts efficiency; however, without this, our cloth behaved erratically and would stretch too much, making this method very useful.

4 The Fluid Simulation

For representing our fluid, we used the process described by Foster and Metaxas. Our fluid is simulated in a grid of uniform, cubic cells (in theory, the simulation can be made to handle a grid of uniform rectangular prisms, but we settled on restricting it to grids for simplicity). We populate this grid with a collection of marks that represent the fluid. It is important to note that the marks do not represent the individual fluid particles, but rather where the fluid is and they do not interact with other marks directly. The Mark-and-Cell method is computed using a set of Navier-Stokes equations that calculate the velocity of a fluid based on its current velocity, the current pressure gradient, gravity, and the fluid's viscosity. The velocity of the fluid is represented at the midpoint of each cell boundary. The velocity at this boundary stores only a single dimension of the vlocity at that point. The dimension of this velocity component correlates to the dimension of the boundary on which it lies. This velocity is updated at a time step using Navier-Stokes equations. Then each component of a mark's new velocity is calculated using a weighted average of the four nearest cell velocities that correspond to that dimension. The velocity is then used to determine the mark's new position. Note that we do not store the velocity of a mark as that is derived computationally from the cells.

4.1 Sources and Sinks

Some of the scenes we wanted to simulate required fluid to be able to enter and leave the scene at specified cell faces. We call these faces sources and sinks respectively. In our program, we allow for the user to specify which faces will be sources and sinks by declaring an initial velocity for boundary faces. Depending on the direction, the program will flag that face as a source or a sink. If the velocity is pointing into the scene it is a source and if it points out of the scene it is a sink. Our system locks the velocity of a sink or source to its initial value so that the flow of surrounding fluid does not modify the velocities. If a mark is contacting a sink face, it is removed from the simulation. If the program has the sources toggled on, the source will add new marks to the system at a random point along the source face. The amount of new marks that are introduced depends on the initial density of marks in the simulation as well as another variable specified for the scene that states how often the source should add new marks into the scene.

5 One-Way Coupling

In order to allow the fluid to affect the cloth, we would need to get the force applied to a point on the cloth from the surrounding medium, in this case the fluid. This interaction is defined by Xavier Provot [Provot 1995] in the following equation:

$$F_{fl}(P_{i,j}) = C_{fl}\,(n_{i,j} \bullet (v_{fl} - v_{i,j})\,)\,n_{i,j}$$

In this equation, we use the surface normal of the cloth at particle $\mathbf{P_{i,j}}$, represented as $\mathbf{n_{i,j}}$. We take the dot product of the normal and the difference between the velocity of the surrounding medium ($\mathbf{v_{fl}}$) and the velocity of the particle ($\mathbf{v_{i,j}}$). We then multiply this by the vicosity of the medium ($\mathbf{C_{fl}}$) and the surface normal of the cloth. This gives us the force ($\mathbf{F_{fl}}$) of the fluid on point $\mathbf{P_{i,j}}$. This force is then added to the net force on that point. Most of the variables are available from the cloth itself. All we needed to find was the viscosity of the fluid and the velocity of the fluid at certain point in space. The viscosity is a declared constant and easily accessible. In order to determine the velocity of the fluid, we passed the position of the cloth particle into the function that determines the velocity of a mark depending on its position. When Provot mentions this equation, he declares the velocity of the surrounding medium as a uniform velocity. We were able to use a variable velocity determined by our fluid instead and the results were similar to a uniform velocity with the same viscosity.

6 Future Expansions

6.1 Two-Way Coupling

One future expansion is allowing the solid to interact with the fluid. This would cause greater realism; for one thing, the fluid flow will be slowed or stopped when it hits the cloth. There are two parts to implementing two-way coupling: having the cloth apply force to the fluid, and maintaining accurate pressures on either side of the cloth. The first is fairly simple; [Guendelman et al 2005] proposes one such equation. The second is much harder, as the cloth boundary is constantly moving. Maintaining two separate pressures on either side of a line is difficult when the line does not snap to a grid edge, and can cause aliasing issues. If we were looking to use a quick and unsupported solution, we could apply an opposite force on the fluid, or rather the cells that the cloth uses to determine the fluid's local velocity. This will not prevent the fluid from passing through the cloth so the best we can claim it as is a semi-permeable cloth.

7 Examples

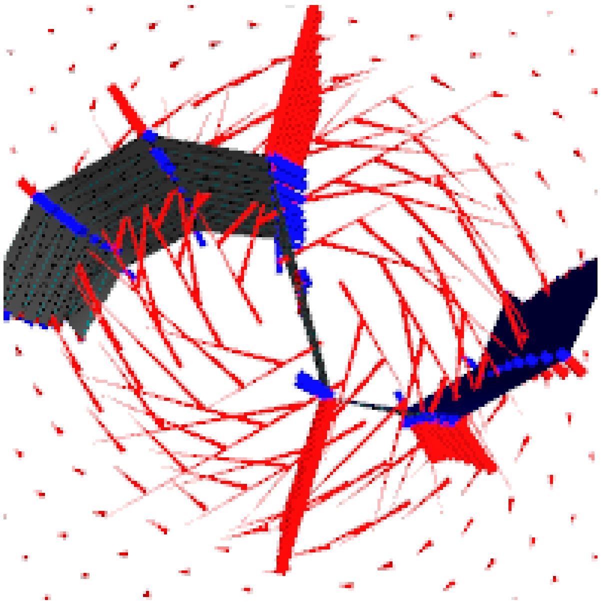
We generated multiple scenes that contain both cloth and fluid. The first two are a small stream of fluid passing through a cloth, the first with gravity applied to both and the cloth being pinned by the top two corners, the second without gravity and all four covers pinned. In both of these scenes the cloth behaved like a sail buffeted by a gust of wind.

Another scene we made one wall entirely source and the opposite a sink. We then aligned a cloth sheet in the expected direction of the flow, fixing the two corners closest to the source wall. As a result the cloth began to behave as a flag would flapping in the wind. The truly interesting part of this scene was that the ripples on the cloth caused by the kinetic energy were palpable in the simulation.

The last scene we tried was placing the cloth in the center of a vertical whirlpool, fixing the central point in place. In this scene, the cloth initially made a symmetrical 'S' shape but then began to crumple in on itself in a chaotic manner. When observed in conjunction with the velocity of the surrounding fluid, it becomes apparent the the cloth will correspond to the velocity gradient of the surrounding fluid. This could be used as an alternative to fluid visualization.

8 Conclusions

Ultimately we were mainly limited in our approach. Others before us [Guendelman et al 2005] had already tried the methods we used and were unsatisfied by the lack of effect on the fluid. As we only set out to implement the fluid's effect of the cloth, we achieved our goal. The most surprising and satisfying part of the program was the fact that our results looked believable despite only implementing half of the system of interactions. We hope that if we were to continue in the direction we are headed, we could develop an alternative two way coupling system.



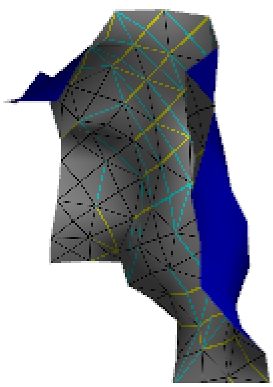


Figure 1 and 2: *Cloth submerged in a vortex. Note at the cloth's inner forces (blue lines in 3) resemble the velocity of the fluid (thin red lines in 3). 4 shows the decomposition of the fluid and the cloth's reaction to this is crumpling up.*

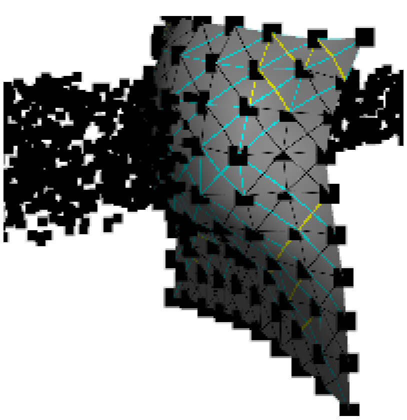


Figure 3: *a jet of fluid going through a cloth. No gravity in this scene. Note how the bottom part is not puffed out.*

9 Division of Labor

Cloth Simulation – Jay Jensen
Fluid Simulation – Kyle Samson (Thanks Barb!)
Sources and Sinks – Kyle Samson
Cloth and Fluid in the Same Scene – Kyle Samson
Fluid Effect on Cloth – Jay Jensen
Test Scenes – Jay Jensen, Kyle Samson

10 References

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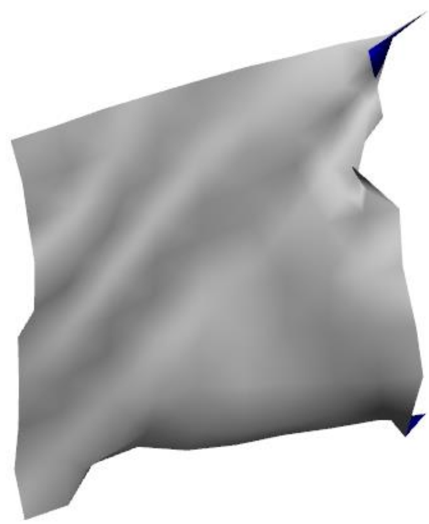

Figure 4: *Cloth in a flowing medium behaving like a flag. The flag has notable ripples.*