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Abstract

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Contents

1	Introduction	8
2	Literature Review	9
2.1	Introduction to Cloth Simulation	9
2.2	Brief History of Cloth Simulation	9
2.3	Underlying Physics	10
2.4	Offline Cloth Simulation	11
2.4.1	Fine Cloth Interactions	11
2.4.2	Precomputing Effects	12
2.5	Real Time Cloth Simulation	13
2.5.1	Mass-Spring Systems	14
2.5.2	Particle-Based Systems	15
2.5.3	Continuum	15
2.5.4	Alternative Methods for Cloth Simulation	15
2.5.5	Position Based Dynamics	15
2.5.6	Extended Position Based Dynamics	15
2.6	Future Trends	15
2.7	Conclusion	15
3	Rest of Diss	16
3.0.1	Overview Of Project Content and Milestones	16
4	Chapter 2	17
5	Additional Information / Knowledge Required	18
	References	19
	Appendices	20
A	Project Overview	20
A.A	Example sub appendices	20
B	Second Formal Review Output	21
C	Diary Sheets (or other project management evidence)	22
D	Appendix 4 and following	23

List of Tables

List of Figures

Acknowledgements

Insert acknowledgements here

I would like to thank my cat, dog and family.

1 Introduction

2 Literature Review

2.1 Introduction to Cloth Simulation

Cloth is a major aspect of realistic simulations. Present in many different industries such as: film, games development and virtual reality, cloth simulation is a challenge that combines maths, physics and programming.

Cloth simulation is a subsection of Physics-based animation. PBA uses physics and code to create a plausible looking display of realistic effects, e.g. fluid simulations, soft-body dynamics etc. Cloth is defined as a flexible plane of some material or fabric that can move in unique ways, such as bending or stretching. This makes it a tricky and unique problem to simulate accurately.

The end goal of a cloth simulation can vary depending on the intended use. In computer graphics, physical accuracy is not the highest priority, the end product is mostly focused on how it looks. This is in contrast to cloth simulations for real-world engineering problems, their focus being primarily on physical accuracy, in order to help them predict real-world scenarios. Real time usage of cloth is also very important in the games industry, and will be discussed later.

As it is featured in such a wide range of fields, the literature relating to cloth is plentiful. In this section, many papers, books and articles will be discussed and compared in order to give context to the focus of this project, Extended position based dynamics (XPBD).

2.2 Brief History of Cloth Simulation

Cloth simulation is a very active field in research, and has been for a handful of decades. The first graphic models used to mimicking cloth was developed in 1986 by Jerry Weil. Before this, cloth objects were created by mapping textures onto rigid surfaces. His method represents cloth as a 2d grid of 3d coordinates, and focused on simulating cloth held at constraint points, like a draped fabric. (Weil, 1986). This method didn't allow for cloth movement but it piqued the interest of the graphics community regarding cloth simulation.

An important development was made in 1987 by Terzopoulos et al. Their method was a general solution for representing elastic deformable objects like

rubber or paper. This method is physically-based, meaning the object is active and can respond to external forces such as gravity or wind. Their paper presented various equations on how objects such as cloth or paper should deform when presented with forces, it also describes how they integrated these equations through time, which is a key topic in simulation. This research laid the groundwork for many more physically based models, and more cloth oriented methods. (Terzopoulos, Platt, Barr, & Fleischer, 1987)

As time went on, more ways to simulate cloth were developed, such as particle based systems by Breen et al. in 1992. In particle-based systems, the simulating focused on a series of connected particles, and how they react with each other. The way these particles interacted formed the basis for the cloth dynamics. (Breen, House, & Getto, 1992) In their paper they decided to move away from continuum based methods and switch towards a particle based model. In 1995, Provot developed a similar particle system but used point masses connected with springs to represent a cloth mesh. (Provot, 1995)

In 1998, Baraff and Witkin developed a method that used implicit integration combined with the cloth being represented as a mesh of triangles. This new proposed system allowed for bigger time steps to be taken and faster simulation times. This system is still used today as the foundation for new methods. (Baraff & Witkin, 1998)

Later, in 2007, Müller et al. developed and published a paper on a state of the art method for dynamic simulations called Position Based Dynamics. This technique, along with a newer extended version, is the main focus of this project and will be discussed in a later chapter. (Müller, Heidelberger, Hennix, & Ratcliff, 2007) and (Macklin, Müller, & Chentanez, 2016)

2.3 Underlying Physics

In order to discuss the advancements and methods within the current literature, it is important to delve into the underlying physics that allow cloth simulations to function. This section will go over important principles that are crucial to creating such simulations.

Often, cloth is represented by particles. These particles have position p , and velocity v , and can be arranged in a grid structure to model a piece of cloth. In order to represent the actual geometry of these particles, they can be arranged into triangles that make up a bigger mesh. When these triangles

are small enough, that is when the simulated cloth can look realistic.

For simulations such as mass-spring systems, forces are the primary mechanism for making the particles move. In this case, spring forces between two particles are calculated using Hooke's law, and they say that if the spring is stretched or compressed more than the springs rest length, forces are applied to remedy that. Other common forces are gravity and wind and these will be applied to near all simulations regardless of if it is a force-based method or not.

As the main focus of this project is position-based dynamics, constraints must be discussed too. Constraints are pivotal to position-based dynamics because instead of relying on forces, PBD directly adjusts positions to satisfy constraints. Constraints can vary depending on the situation but usually there are some staples such as distance, bending and collision constraints. Each of these will ensure that the particles within the simulation act as realistic as possible.

2.4 Offline Cloth Simulation

Cloth simulation can generally be split into two categories: Offline and Real Time. Offline simulations are calculated, tweaked and edited before being rendered to the screen. Commonly used in film and animation, visual fidelity is of utmost importance. Offline calculations can also help in a real time scenario by precomputing effects.

2.4.1 Fine Cloth Interactions

As offline simulations are not limited by the time between each frame, they can afford to focus on realism. They can do this by scaling the number of triangles up and allowing for finer interactions like folding and wrinkling, these interactions being crucial to a convincing cloth simulation. A great example of such work is presented in a paper by Selle et al., they detail their method of creating a high resolution simulation with up to two million triangles, that can accurately capture the intricate details of cloth. (Selle, Su, Irving, & Fedkiw, 2009)

At the time of publication, cloth simulations were adding physically-based interactions like wrinkles through a separate modelling system. This can be seen in the work by Cutler et al., in which they created a system that al-

lowed the artist to add in wrinkles on top of an existing character's clothing (Cutler et al., 2005). They achieved this by splitting it into stages: wrinkle creation and wrinkle evaluation. In the wrinkle creation phase, the artists use a tool to create wrinkle patterns, which get turned into a set of forces on the surface. Next, in the wrinkle evaluation phase, the system generates these deformations based on character poses, and the artists can either choose to keep these generated wrinkles, or alter the pattern until satisfactory results are achieved.

In their results, they were able to use their system to create clothing wrinkles on hundreds of characters for a feature-length animated film. They noted that in production, close to zero hand-tweaking was needed for the wrinkles, proving its reliability.

When discussing their work, they did note that the visual results from a dynamic clothing simulation is much preferred to what they achieved with their kinematic wrinkle system. This is where the work of Selle et al., aims to improve upon.

In their paper, they aimed to create a system where fine details such as folds and wrinkles were created in a physically-based fashion, from the various forces acting on the cloth. Their setup included a mass-spring system with edge and bending spring, and a modified time integration scheme. One notable contribution from their work is how they handle collisions. They note that in order to achieve high resolution folds and wrinkles, the self collisions and interactions must be extremely robust, as they are what cause cloth to create these effects in the first place. In their paper, they created a hybrid repulsion/collision technique that works based on the last known collision. They also utilise parallelism to further improve computing times.

In their initial evaluation, the researchers put their system to the test with a twisted cloth model comprising 500,000 triangles. This example took an average of 30 minutes to calculate each frame. They found that their system was able to simulate an extremely detailed cloth with accurate folds and wrinkles, alongside realistic collision and repulsion. These advanced and realistic effects lend themselves to the offline nature of the simulation, as calculating all of these effects are extremely computationally expensive.

2.4.2 Precomputing Effects

In computer graphics, it is often said that precomputing everything is simply not viable due to how many interactions can occur, but in a paper by Kim et al., they discuss precomputing secondary cloth effects. (Kim et al., 2013). In this case, secondary cloth effects refer to things such as folds and wrin-

kles, these are expensive simulate in real-time. In this paper, they propose a method to use many thousand CPU-hours to calculate these advanced effects in advance, based on a character motion graph. They achieve this by representing a character with two motion graphs, the primary graph simply being the movement of the character, and the secondary being the cloth dynamics.

To evaluate their method, they acquired 12 unique motion clips for the primary graph, and used ARCSim cloth simulator for the cloth motion. They found that in their massive precomputation, they were able to generate good looking cloth animations for any random paths through the primary graph. Initially their secondary graph was just one to one mapping of character poses to cloth, but this proved insufficient for realistic motion, so the secondary graph was made much more complex. Overall, the inclusion of precomputing cloth motion, helped simulate incredibly detailed secondary features of cloth, such as wrinkles and folds. This research also links into game development in their discussion section, they propose that viewing a database of precomputed cloth motion could be a great benefit when creating games, as certain scenes could be viewed and edited, also bad looking cloth could be fixed by hand to help realism within the game.

In summary, it can be seen that offline simulations, compared to real-time, prioritise visual plausibility and realistic effects. These simulations can be achieved due to their non-real-time nature, being able to compute all necessary effects in advance, and being able to tweak things that don't quite match with others. Making offline simulations great for things such as: animation, fashion design and the film industry. This level of details contrasts with real-time simulations, where they must balance out visual quality with the demands of immediate computation.

2.5 Real Time Cloth Simulation

Real time cloth simulations are created by computing the cloth dynamics at runtime, allowing interaction with the user through input and changes from the environment. As the time between frames on real time applications is small, the dynamics need to be calculated and applied efficiently, usually on the GPU. The most common use case for real time cloth simulations are in video games, and as these games also have lots of other calculations going on in the background, means optimisation is even more important. This section will discuss the literature on methods to create these simulations and how they compare with each other.

2.5.1 Mass-Spring Systems

As mentioned in the physics section, mass-spring systems are a popular approach to cloth simulations. They represent a cloth as a grid of particles that can exert forces on each other. The way they exert forces are through springs. As mentioned in the history of cloth simulation section, the first example of this system was introduced by Provot (Provot, 1995).

In his paper, he posited that the current state of cloth animation at the time had a lack of realism, especially in the realm of elasticity. His proposed mesh had three different types of springs to achieve different effects. Structural springs being the most basic, it connects adjacent particles in a grid formation. Shear springs connect particles diagonally, and bend springs connect particles by skipping a particle in between, e.g. connecting particle $[i,j]$ to particle $[i+2,j+2]$.

This research successfully modelled a more realistic cloth using mass-springs and inspired research into more efficient mass-spring systems for use in real time, such as the work by Kang and Cho (Kang & Cho, 2012). It is known that the mass-spring model suffers from instability, especially at larger time steps, Kang and Cho aim to resolve this instability by proposing a more stable and accurate integration model. They note that an implicit integration scheme would help stabilise the system but it cannot be easily parallelised, so an improved explicit method was chosen.

It is noted that Hooke's law is commonly used with mass-spring systems to calculate forces, but Kang and Cho decided to use a harmonic oscillation model, allowing for integration.

With their new integration method and parallelism implemented, they were able to simulate cloth containing 16,384 particles and 161,544 springs at over 68 frames per second. This shows that mass spring systems can be a good tool for simple simulations, although in their results they also show that once the springs get to a large size, in this case 1,200,000 springs, the frame rate drops to 15. It can be seen in current day simulations that the additional complexity from all the springs, stiffness tuning and overall accuracy lead to mass-spring systems not being the optimal method for real time cloth simulations.

2.5.2 Particle-Based Systems

2.5.3 Continuum

2.5.4 Alternative Methods for Cloth Simulation

2.5.5 Position Based Dynamics

2.5.6 Extended Position Based Dynamics

2.6 Future Trends

2.7 Conclusion

3 Rest of Diss

3.0.1 Overview Of Project Content and Milestones

This is a sub sub section with a list of bullet points.

- A working X, that will be used for this investigation.
- Investigation of current tools and their potential use during an investigation of X .
- Programming of X with related frameworks Y and Z.
- That is all.

4 Chapter 2

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5 Additional Information / Knowledge Required

Experience with Linux and managing Virtual machines, networking. So on and so forth...

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Appendices

A Project Overview

A.A Example sub appendices

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B Second Formal Review Output

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C Diary Sheets (or other project management evidence)

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D Appendix 4 and following

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