
Real-Time Cloth Simulation using Extended Position Based Dynamics

Matthew Lenathen -
40506678

Submitted in partial fulfilment of
the requirements of Edinburgh Napier University
for the Degree of
BSc (Hons) Games Development

School of Computing

April 16, 2024

Authorship Declaration

I, Matthew Lenathen, confirm that this dissertation and the work presented in it are my own achievement.

Where I have consulted the published work of others this is always clearly attributed;

Where I have quoted from the work of others the source is always given. With the exception of such quotations this dissertation is entirely my own work;

I have acknowledged all main sources of help;

If my research follows on from previous work or is part of a larger collaborative research project I have made clear exactly what was done by others and what I have contributed myself;

I have read and understand the penalties associated with Academic Misconduct.

I also confirm that I have obtained informed consent from all people I have involved in the work in this dissertation following the School's ethical guidelines.

Signed: 

Date: 16/04/2024

Matriculation no: 40506678

General Data Protection Regulation Declaration

Under the General Data Protection Regulation (GDPR) (EU) 2016/679, the University cannot disclose your grade to an unauthorised person. However, other students benefit from studying dissertations that have their grades attached.

Please sign your name below one of the options below to state your preference.

The University may make this dissertation, with indicative grade, available to others.



The University may make this dissertation available to others, but the grade may not be disclosed.

The University may not make this dissertation available to others.

Abstract

Real-time cloth simulation, a subset of physics-based simulations, aims to generate realistic simulations of cloth-like objects using mathematics, physics, and programming. It is a complex problem to solve and many specialised methods have been developed to further the realism, while aiming to lower the computational cost. This project details the implementation of a popular cloth simulation method, extended position based dynamics, in the Unity physics framework. The Unity framework was useful in allowing features such as user interaction and experiment recording, which in turn allowed for greater testing of the methods. The implementation is compared to two other cloth simulation methods, the mass-spring system and the original position based dynamics. These three methods will be tested in various scenarios and experiments to analyse the effectiveness of these methods in simulating realistic cloth dynamics. The two key scenarios are a vertical cloth object pinned by two points, and a horizontal cloth falling on top of a rigid sphere. These were chosen as they effectively demonstrate how the cloth would move in potential projects such as games or animation. It was found that extended position based dynamics is a powerful and relatively inexpensive method to use, and improved upon position based dynamics in a few ways. One such way was decoupling the stiffness of the cloth, from the number of substeps within the simulation, a flaw that the original position based dynamics had.

Contents

1	Introduction	9
2	Literature Review	11
2.1	Introduction to Cloth Simulation	11
2.2	Brief History of Cloth Simulation	11
2.3	Underlying Physics	12
2.4	Offline Cloth Simulation	13
2.4.1	Fine Cloth Interactions	13
2.4.2	Precomputing Cloth Effects	14
2.5	Real Time Cloth Simulation	15
2.5.1	Mass-Spring Systems	16
2.5.2	The Continuum Model	17
2.5.3	Cloth Simulation with Camera Capture	18
2.5.4	Cloth Simulation with Neural Networks	19
2.5.5	Shape Matching	21
2.5.6	Position Based Dynamics	23
2.6	Future Trends	29
2.7	Conclusion	29
3	Methodology	31
3.1	Environment and Framework	31
3.1.1	Language Choice	31
3.2	Initialisation	33
3.2.1	Mesh Creation	33
3.2.2	Particle Class	34
3.3	Mass-Spring System	35
3.4	Position Based Dynamics	37
3.4.1	Constraints	39
3.4.2	Updating Position and Velocity	41
3.5	Extended Position Based Dynamics	42
3.5.1	Substeps vs Solver Iterations	42
3.5.2	Stiffness through a Compliance Factor	42
3.6	User Cloth interaction	43
3.7	Cloth and Sphere Collision	44
4	Results and Discussion	46
4.1	C++ vs C#	46
4.2	Recording Feature	49

4.3	Scenarios	49
4.3.1	Hanging Cloth	50
4.3.2	Cloth falling on Sphere	55
4.4	Discussion	56
5	Reflection	59
6	Conclusion	61
	References	62
	Appendices	66
A	Project Overview	66
B	Second Formal Review Output	68
C	Diary Sheets	70
D	Poster	77

List of Tables

1	Frame time comparison between C# and C++ for a mass spring system of 20x20 particles	46
2	Frame time comparison between C# and C++ for a mass spring system of 100x100 particles	47
3	Frame time comparison between C# and C++ for a mass spring system of 150x150 particles	47
4	Substeps and Frame Time Data	54

List of Figures

1	An overview of a neural network cloth model	20
2	Two levels in a multi-resolution configuration, where a is a nested model and b is a non-nested model.	22
3	The simulation remaining stable in high wind speeds	28
4	A wireframe of a vertical cloth mesh	35
5	The types of springs typically used. Figure adapted from (Va, Choi, & Hong, 2021).	37
6	Projection of a constraint between two particles. Figure adapted from (Müller, Heidelberger, Hennix, & Ratcliff, 2007).	40
7	Hanging cloth mesh being dragged by a corner particle	44
8	Average Frame Time for C# and C++ in a Mass Spring System	48
9	The folder of experiment recordings.	49
10	Three versions of the mass spring system, with spring con- stants of 500,1000 and 1500 left to right	51
11	Testing the time step stiffness issue with original PBD, with time steps of 0.04, 0.02 and 0.01 left to right	52
12	Cloth with different stiffness values	53
13	Time step stiffness problem resolved in XPBD	55
14	Z-fighting issue when rendering two colliding objects	56
15	The glass sphere approach to solve z-fighting	56

Acknowledgements

I'd first like to thank my supervisor Dr Babis Koniaris for all his help during this project and throughout my time at Napier.

I'd also like to thank my family and friends for encouraging me.

1 Introduction

This project aims to cover the implementation of a realistic cloth simulation within the Unity physics framework. Cloth simulation, a subset of physics-based simulations, aims to combine the principles of mathematics, physics and programming to realistically simulate cloth-like objects and how they interact with external forces. It is used in many industries such as games development, film and animation, and virtual reality based applications. For decades, researchers have been designing new methods of accurately simulating cloth, while aiming to keep computational cost to a minimum. One such method is known as position based dynamics (PBD), with a further extension called extended position based dynamics (XPBD). This project is focussed on the overall implementation and testing of XPBD within Unity, a popular games development tool that also functions as a physics simulation framework. Unity was chosen as the framework of choice, as it is very popular and has a vast amount of documentation online which was helpful when implementing my own features within it. Unity typically uses C# for its scripts but this simulation was written as a C++ dll, as C++ is much more memory efficient and optimised for programs that have lots of computation. This will be discussed more in Section 3.1.1.

Cloth simulation is a challenging topic of physics based simulations, as it often requires many parameters and tweaking of these parameters to accurately simulate real life cloth dynamics such as bending, stretching and shearing. Three methods will be implemented: Mass-spring system, PBD and XPBD. Mass-spring systems work by considering the connections that make up the cloth, as springs. This is a simple method to implement but falls short in modern cloth simulations as it can often become unstable and inaccurate. Position based dynamics considers the cloth as a mesh of particles that have constraints between them. These constraints aim to keep the neighbouring particles a set distance away from each other, and will help move these particles to satisfy the constraints. PBD is a very efficient method, and while not completely physically accurate, it gets close enough for most applications. PBD falls short when dealing with cloth stiffness, the way the algorithm is designed means that the stiffness of the cloth is linked to the number of solver iterations. Solver iterations represents the number of times the constraints are worked on during one time step. Meaning that if the time step decreases, the constraints get arbitrarily stiff. This is a problem as it requires the developer to manually tune the simulation for different time steps, requiring much more work. This is one of the reasons XPBD was

created, to decouple the constraint stiffness from the time step.

XPBD works by splitting each time step into substeps, and solving the constraints once per substep. The authors of PBD and XPBD found that spending the fixed time budget using substeps was more computationally efficient than using solver iterations in PBD. XPBD also improves the stiffness by changing the 0 to 1 range in PBD, to a compliance factor that allows constraints to be infinitely stiff at compliance = 0, while allowing a smooth range of compliance values that will suit a wide range of scenarios.

The goal of this project is to successfully implement these methods and test them against each other, while varying parameters such as time step, substeps and stiffness. It does this through the use of two scenarios: a vertical cloth pinned by two points and a horizontal cloth falling on a sphere. The cloth meshes used for these scenarios were generated in the C# script, this allowed for easy tweaking of overall mesh size, which is useful for experiments. One of the main ways of measuring the performance of a cloth simulation is through frame time. Frame time is a commonly used metric in real time rendering, and it represents the time to render one frame. It is much preferred over FPS as the overall FPS of a simulation can be misleading, e.g. a simulation can have stable fps, but if the frame time differs heavily, it will result in stuttering that is unwanted in real time applications.

The first chapter of this dissertation will dive into the literature surrounding cloth simulation. It will discuss the history of cloth simulation, the underlying physics before going on to cover many methods for use in both offline and real-time cloth simulations, and how they work. The next chapter discusses the methodology behind this project, the design choices and how the methods were implemented in code, along with other features such as user interaction and the experiment recorder. It will then cover the results obtained from many experiments done on these three methods. It will go into depth on scenario setups and experiment parameters, to effectively analyse how each method performs. Finally, a reflection of the overall project, discussing both the achievements and shortcomings of the overall simulation.

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 challenging 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 et al., 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 Cloth 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. (D. Kim et al., 2013). In this case, secondary cloth effects refer to things such as folds

and wrinkles, 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 section 2.3, 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. The first example of this system, as noted in section 2.2, 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 The Continuum Model

While representing cloth with particles and springs can be straightforward and relatively pleasing to look at, there is a downside to this method, the real world representation of cloth. It is very hard to come up with a spring model that accurately represents various cloth materials such as nylon. This is where the continuum system for cloth fits in. The continuum method treats cloth as a continuous material made up of triangles rather than particles with space in-between, and instead of looking at spring forces, continuum looks at how each triangle is stretched and compressed.

As mentioned in section 2.2, Baraff and Witkin proposed one of the first continuum models in their paper (Baraff & Witkin, 1998). A few others attempted such models such as (Terzopoulos et al., 1987). Although in their implementation, the damping forces weren't explored in much depth. Another paper by (Carignan, Yang, Thalmann, & Thalmann, 1992) built upon the work by Terzopoulos et al. and improved the damping forces by adding a force that damps cloth stretch and shear. They used an explicit integration scheme so was unfortunately limited by small time steps. These works lead Baraff and Witkin to develop their model. Their goal was to come up with a method that allows for larger time steps to be taken in simulation, as most at the time were bottlenecked by small time steps to remain stable. In their method, they employ an implicit integration scheme which allowed for much better performance, when combined with the simple formulation of internal forces. With this continuum representation, they were able to successfully model the common forces like shearing, bending and stretching.

In their results, they tested multiple setups including clothing. They found that changing the bend stiffness factor, didn't affect in running times a great deal, which explicit simulators wouldn't be able to do. They were also able to estimate their performance in terms of number of particles, and found that it was slightly better than $O(n^{1.5})$ which was what they expected.

This paper laid the groundworks for many continuum implementations, one of which being a paper on data-driven elastic models for cloth simulation (H. Wang, O'Brien, & Ramamoorthi, 2011). Their goal was to more closely represent how different materials are simulated, ideally close to their real world counterpart. It does this by representing cloth with a piecewise linear elastic model. They explain that real world cloth items such as clothes often have anisotropic properties from the woven nature of cloth, and that this is often ignored by most cloth simulations for simplicity. A part of their re-

search was a way to measure real life samples of cloth, construct a database of parameters and use them directly in their cloth simulation which was a very interesting way to get realistic results.

Finite element analysis is a way to break down the cloth into discrete elements such as triangles, and the physical behaviour is calculated based on the material properties and forces acting on it. In 2020, Kim discussed how most cloth simulation are either made from finite element methods, position based dynamics or mass-spring systems, and that the Baraff-Witkin model doesn't really fit into these categories. In his paper he formulated a version of the Baraff-Witkin model but entirely in terms of finite elements (T. Kim, 2020).

2.5.3 Cloth Simulation with Camera Capture

As cloth simulation is such a wide field of research, there are many alternative methods and interesting papers to look at, one such idea is SimulCap by (Yu et al., 2019). SimulCap is a method of capturing human movement while also capturing dynamic details such as folds and wrinkles. It uses a RGBD (RGB depth) camera. Their problem with other recent implementations were the lack of realism, in part due to the human and cloth being considered as one piece of geometry, and also the results not being editable, which is a huge aspect of a lot of use cases, i.e. virtual dressing applications. So, for SimulCap, the authors decided to combine a layered representation of the human body, while also having a separate cloth simulation that matches the human movement. For their cloth simulation, they chose to use a mass-spring model for simplicity and also an explicit integration scheme with a small time step for stability. In their results, they compared their implementation with DoubleFusion, another previous system by (Yu et al., 2018), which is a state-of-the-art system for real time human capture. The authors found that SimulCap achieves a much more realistic cloth representation, mainly due to the separation of geometry as described earlier. The limitations of this system lie in the variation of clothing, e.g. thick jumpers remain challenging to simulate, also due to the simple nature of the cloth simulation, the realism could be improved upon by choosing a more advanced technique.

In a more recent paper by Wang et al., in 2023, they address the problem of extracting cloth movement combined with clothing motion, by proposing a novel method of capturing the human motion and clothing separately using double layer neural radiance fields (NeRF) (K. Wang, Zhang, Cong, & Yang,

2023). NeRF is a method of reconstructing a 3D scene using sparse 2D images. This makes it a perfect method for cloth simulation using camera capture. During the optimisation phase, they introduce a physics-aware cloth simulation network to properly handle the cloth dynamics to ensure realism.

They comment on the previous implementation, SimulCap, by saying it failed to track the motion of the clothing to achieve editable clothing on humans, which is a prerequisite to most VR/AR apps. Their solution, using NeRFs, model both the body and the clothing in template space, which can then be transformed into observation space using deformation fields. Then, using the two NeRFs from before, the rendered images can be synthesized.

This approach addresses the problems with previous camera capture implementations. Its physics network is taught from simulation data, to constrain the clothing and ensure physically plausible clothing deformations. In their comparison to state of the art methods, which include DeepCap and NerfCap, they found that their implementation vastly outperformed the other methods without a cloth template, and achieved a much higher accuracy during geometry tracking.

2.5.4 Cloth Simulation with Neural Networks

Another interesting alternative method to cloth can be found in the research of (Bertiche, Madadi, & Escalera, 2022), a cloth simulation framework that uses an unsupervised deep learning methodology. This has been attempted in the past but the other approaches do not handle cloth dynamics. The authors note that while supervised learning systems have been used before, it requires huge volumes of data, and it has to be repeated for every garment/body, so they chose an unsupervised approach. For their cloth representation, they chose to use a particle based system that also considers external forces like wind and collision, this cloth is then skinned to a 3D model. After training their model, they compared their results to other unsupervised approaches such as (Bertiche, Madadi, & Escalera, 2021). They evaluated their framework with multiple different body motions such as jumping and spinning. They found that their approach was the only one capable of achieving dynamic cloth effects. In terms of limitations, unsupervised learning compared to supervised takes much longer and is more computationally expensive, and neural cloth has yet to implement cloth self-collision which is a crucial component of most simulators.

Another example of cloth simulations using neural networks can be found in the works of Oh et al., where they propose a hierarchical cloth simulation method that combines traditional physical based methods with deep neural

networks (DNN) (Oh, Lee, & Lee, 2018). They note that proper physically based cloth animation is expensive, so being able to utilise DNNs to replace the complex computation with data inferred from the network will reduce the cost significantly.

Their proposed method would split the simulation into two parts. Firstly, a low resolution or coarse model of the cloth is calculated using a normal physically based method. Then, the DNN is used to calculate the finer levels of the cloth, reducing the computation cost. They note that due to only calculating the coarsest level of cloth using a physically-based method, the overall cloth simulation won't be as accurate as a fully physically-based model but it successfully prevents errors stemming from the DNN, and guarantees a reliable simulation. This can be seen in Figure 1.

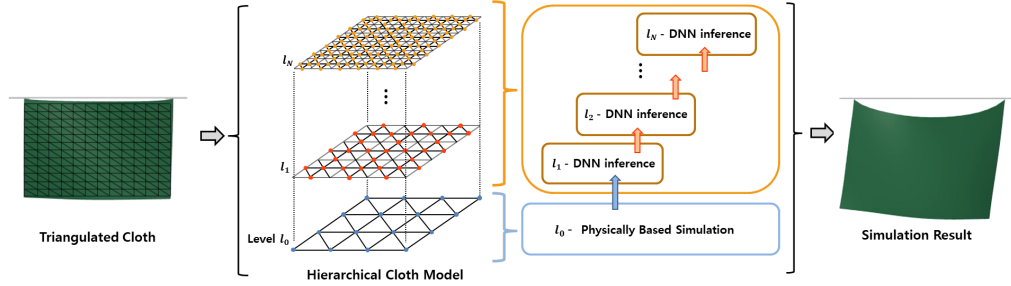


Figure 1: An overview of a neural network cloth model

In their results, they constructed the simulation with three levels, one physically based used projective dynamics, and two DNN models. Projective dynamics will be covered in section 2.5.6. They compared time performance of their method against a normal implicit integration simulation, and against a projective dynamics implementation with an optimised algorithm applied to it called ADMM (alternating direction method of multipliers) (Narain, Overby, & Brown, 2016). They found that their hierarchical model that uses DNN improved performance, especially on configurations with many particles, e.g. flags and curtains. They do admit that the accuracy is not on the same level as completely physically based implementations but the results generated were of a high standard and were fast to generate. One final thing to note is that if the cloth is overstretched by external forces, the DNN can sometimes give unusual wrinkles near the bottom of the cloth. They aim to improve this in future work by updating the DNN model to also hold information such as velocity and momentum.

2.5.5 Shape Matching

Shape matching is a technique that allows an object to deform but tries to maintain the form of the original shape. In 2005, Müller et al., utilised shape matching to come up with a new method to simulate deformable objects (Müller, Heidelberger, Teschner, & Gross, 2005). It does this by replacing energies by geometric constraints, and forces by the distance of current positions to goal positions. These goal positions are determined by shape matching, given a rest state. They mention that because the points are always drawn to goal positions, the overshooting issue with explicit methods is completely removed.

In their algorithm, their idea is given a set of particles with an initial configuration, every time step the particles are moved towards their goal position, and these goal positions are determined by the original configuration of the shape. In terms of performance, it depends on the number of points used, and they note it is hard to compare it to another model such as mass-spring systems, as the technique depends on the number of clusters chosen, which cannot be reflected in the other models.

Overall, this shape matching approach to simulation provides an unconditionally stable simulation that is inexpensive to compute, although the model is not physically accurate.

This research inspired a paper on cloth simulation using shape matching in 2013 (Bender, Weber, & Diziol, 2013). As mentioned before, using shape matching for simulations proved unconditionally stable, so a model specifically designed for cloth simulation was created. They note that normal shape matching approaches that use regions, cannot differentiate between shearing, bending and stretching, which are crucial to represent cloth accurately. To combat that, they introduce a novel approach to use a multi-resolution model instead of region based. This can be seen in Figure 2, where a is a nested model that shares vertices between levels, and b is a non-nested model that do not share vertices. The results in this paper use a nested configuration. This multi-resolution model will allow for the simulation of fabrics that have different stretching/shearing stiffness. It is also noted that this method is fast due to it scaling linearly with the size of the cloth.

A shape matching approach that used regions was attempted before (Stumpp, Spillmann, Becker, & Teschner, 2008). But in this model, it introduces forces that influence the bending stiffness and depend on the size of the model, and this is undesirable in cloth simulation. Another problem is

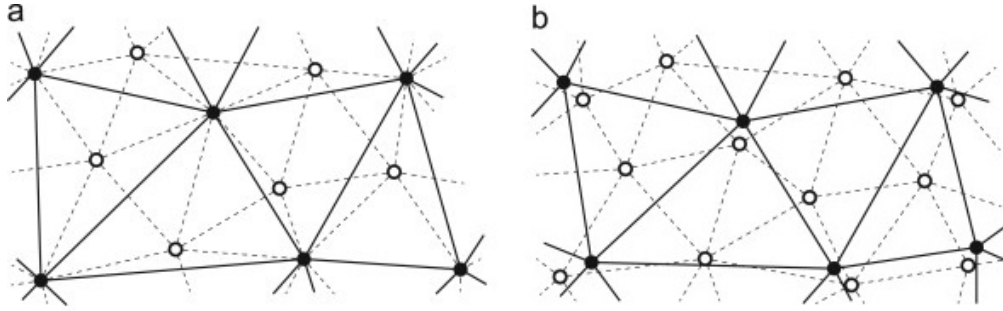


Figure 2: Two levels in a multi-resolution configuration, where a is a nested model and b is a non-nested model.

that due to small regions within a large model, high stretching and shearing stiffness cannot be obtained. This led to the development of the multi-resolution approach.

In terms of performance, they simulated meshes between 10000 and 100000 triangles to test their scalability, and confirmed their linear relationship between computation time and number of triangles. They also implemented a GPU version of the method which resulted in a much faster compute time. They found in similar setups, the multi-resolution method was around 9 times faster than a standard mass-spring system, and around 15 times faster than a corotational finite element method, a method created by Etzmuss et al. (Etzmuß, Keckeisen, & Straßer, 2003). Overall, the multi-resolution approach provided a very noticeable speed-up compared to other approaches, at the cost of physical accuracy.

Another implementation of shape matching was proposed by Vassilev, using shape matching to improve upon a traditional mass-spring model (Vassilev, 2017). Once shape matching is applied, the springs no longer follow Hooke's law but the stability of the simulation is much improved at larger time steps. At the base, this model is based on the work of Provot, discussed in section 2.5.1 (Provot, 1995). The modification made is replacing Hooke's law with shape matching. Vassilev was inspired by the work of Müller et al, in their original shape matching paper, but instead of shape matching on regions of vertices, Vassilev used it on springs. Each mass connected by one spring will have its own goal position to try to achieve.

After implementing it in OpenGL with compute shaders, the implementation was tested on a human figure wearing jeans, to monitor the stability of the shape matching springs. He found that for low time steps, the number of iter-

ations that the shape matching method took to stitch the jeans was roughly the same or slightly higher than the original mass spring model. Since the original model is not stable for time steps above 40ms, the shape matching implementation proved better for larger time steps.

Overall, he found that the shape matching spring implementation was considerably more stable and was less dependant on time steps than the original mass spring system. He proposed this method could be used in real time simulation for things such as trying on clothes on models.

2.5.6 Position Based Dynamics

A great number of techniques discussed above have been force based, and these forces are used to calculate accelerations. Finally these accelerations are integrated to find the velocities and positions of particles. The Position based dynamics (PBD) technique takes a unique approach to physically based animations by omitting the velocity layer and directly working on the positions of particles. (Müller et al., 2007) The main advantage is the controllability, the integration instability discussed in section 2.5.1 is completely avoided due to the lack of explicit integration. As this is a real time technique, it is greatly suited to games development, as it is very helpful to have direct control over positions of objects within the game.

It was noted that even though PBD was the first fully position based approach, there had been other attempts to utilize positions in this way, such as (Jakobsen, 2001). In his approach, Jakobsen manipulated the positions directly using a Verlet integrator. The authors mention that Jakobsen didn't go into depth in terms of constraints, which is crucial in cloth simulation. PBD aims to improve upon it by giving a general approach to constraints.

To fully discuss the technique, the algorithm must be analysed. In the algorithm, an object is represented by N vertices and M constraints. The vertices are the particles which have mass m , position x and velocity v . The constraints contain a few more properties: cardinality, a function, set of indices, stiffness and a type of either equality or inequality. It is noted that the equality property is satisfied if the function of that constraint is equal to 0, and likewise if it has type inequality, it is satisfied if the function is more than equal to zero. The stiffness affects the strength of the constraints and it ranges from 0 to 1.

Algorithm 1 Position Based Dynamics Algorithm

```

1: for all vertices  $i$  do
2:   initialize  $x_i = x_i^0$ ,  $v_i = v_i^0$ ,  $w_i = 1/m_i$ 
3: end for
4: loop
5:   for all vertices  $i$  do
6:      $v_i \leftarrow v_i + \Delta t w_i f_{ext}(x_i)$ 
7:   end for
8:   dampVelocities( $v_1, \dots, v_N$ )
9:   for all vertices  $i$  do
10:     $p_i \leftarrow x_i + \Delta t v_i$ 
11:   end for
12:   for all vertices  $i$  do
13:    generateCollisionConstraints( $x_i \rightarrow p_i$ )
14:   end for
15:   loop solverIterations times
16:    projectConstraints( $C_1, \dots, C_{M+M_{coll}}, p_1, \dots, p_N$ )
17:   end loop
18:   for all vertices  $i$  do
19:     $v_i \leftarrow (p_i - x_i)/\Delta t$ 
20:     $x_i \leftarrow p_i$ 
21:   end for
22:   velocityUpdate( $v_1, \dots, v_N$ )
23: end loop

```

Now it can be broken down to see what each part does. Lines 1 to 3 is just initialising each particle with initial position, velocity and inverse mass. Line 6 is where external forces get added to the system, Müller et al. notes that if gravity is the only external force then the line becomes $v_i \leftarrow v_i + \Delta t g$ where g is the gravitational acceleration. Next, on line 10, the new positions are estimated with a explicit Euler integration step, they are then adjusted in the line 15 loop as many times as needed until all constraints are satisfied. Once completed, the line 18 loop then moves the positions to the calculated position and updates the velocity.

This algorithm can be classed as unconditionally stable as the integration method in lines 19 and 20 do not use future positions/velocities, but instead calculate physically possible configurations and move the vertices to them.

In the paper, the authors also discuss their implementation of a cloth simulator for use in games. Their simulator accepts a triangle mesh and creates two constraints, stretching and bending constraints. Much like the springs in mass-spring systems, these constraints force the positions of the particles to satisfy them in order to continue the simulation, this relates to the loop in line 15 of the algorithm.

To test their cloth simulation, they integrated the method into a game environment and conducted various experiments. They note that a positive to this method is that their bending and stretching terms are independent which can lead to more results when testing values.

In one of their tests they used one way coupling to link cloth to a stationary object, and two way coupled the bottom of the cloth to a rigid body, it resulted in realistic twisting and swaying, but more importantly ran at more than 380fps which showcases the efficiency of this method.

They were also able to test tearing of the cloth. Their tearing process is as follows: when an edge stretches past a threshold value then it is split, with the triangles above being assigned to the original vertex and the lower triangles assigned to the duplicate. They claim this is also extremely stable.

Overall, this paper was a very interesting approach to cloth simulation at the time, and influenced a great deal of work into real time cloth, eventually being used in Nvidia's physX software which in turn is used very frequently in game development.

Extended Position Based Dynamics

In 2016, Müller collaborated with Miles Macklin and Nuttapong Chentanez to extend position based dynamics and improve upon the original method

(Macklin et al., 2016). Their problems with the original stemmed with iteration count and time step affecting the stiffness of the simulated object, specifically: constraints become stiff as iteration count increases/time step decreases. This effect is discussed in the 2014 survey on position-based methods (Bender, Müller, Otaduy, Teschner, & Macklin, 2014).

Their solution to this problem involved creating a new constraint formulation that corresponds to elastic potential energy. It also introduces a total Lagrange multiplier, which is a technique used to find the local maxima and minima of a function that is subject to constraints, e.g. in cloth this could be a distance constraint. This Lagrange multiplier allows the constraints to be solved irrespective of time step.

To test this on cloth, they set up the same cloth configuration for PBD and XPBD and compared them. They found that PBD became progressively stiffer as the iteration count increased but XPBD remained consistent. They also found a small downside of XPBD in terms of performance per-iteration, but this was less than 2% of total simulation time.

In the limitations, the authors note that the method is only an approximation of an implicit Euler integrator, but this still creates very realistic real time results. Even so, if the application requires great accuracy, it would be advisable to choose a more traditional simulation method.

Other PBD methods

In 2012, Kim et al., tackled a problem that all cloth has to deal with: inextensibility (T.-Y. Kim, Chentanez, & Müller-Fischer, 2012). At the time, existing methods had to solve non-linear systems which are computationally expensive. The authors proposed a new method, long range attachments (LRA). It is designed with the fact that in computer games, cloth is typically attached to the kinematic body of whatever is wearing the cloth. It uses this to create a constraint and enforce global inextensibility. This method can be applied to existing physics methods such as position based dynamics.

This works by creating a constraint on a fixed point, e.g. the part of cape attached to a characters shoulders. It then computes the distance from this particle to other attached particles. If a particle goes beyond a certain radius it is projected back towards the surface of a sphere with the centre of that sphere being the attachment point.

The time taken to handle these LRA constraints scales linearly with the

number of attachment points. This can be used to optimise the simulation by pruning certain attachment points. For example, in their cape test, they only choose the closest attachment point to each particle and it shows good results. It gets difficult when working on other shapes and for each configuration, it is recommended to find certain groups of pinned points, e.g. a waistline for a skirt.

In their results, they found that the implementation provided a efficient and simple way to solve the stretching problem of cloth in games. They note that this method is only applicable to cloth applied to characters such as dresses, skirts and capes and that any environmental cloth such as a tissue or paper would see no benefit.

Another interesting approach to position based dynamics is found in the works of Bouaziz et al. (Bouaziz, Martin, Liu, Kavan, & Pauly, 2014). They worked on bridging the gap between position based dynamics, a fast physically inaccurate method, and finite element methods. This lead to robust and efficient implementation that was accurate and supported many different types of constraints. Since continuum methods have the unfortunate side effect of being considerable more expensive than other methods, it would be beneficial to have the accuracy of finite element methods with the efficiency of position based dynamics, this is what projective dynamics aims for. The way they achieve this is by instead of using typical constraints found in position based dynamics, they use constraints derived from continuous deformation energies. With this method they can also perform a local and global optimisation step, meaning that for each element, they project it onto the constraint goal, and at the end the global step combines all of these and finds a compromise.

This is similar to shape matching, which the authors note. (Müller et al., 2005). Except in shape matching, the constraint projections are used to create the elastic forces instead of potentials.

When comparing this implementation to PBD, the authors note that the stiffness due to time step problem in the original PBD is solved due to including a momentum term. So that the cloth can behave in a similar way no matter the chosen time step.

When analysing the results, they test a cloth setup as a flag on a pole, which can be seen in Figure 3. They used edge constraints and external wind force to simulate movement. They were able to simulate the flag tearing in high wind by removing edge constraints when the strain on the cloth exceeds a certain limit.

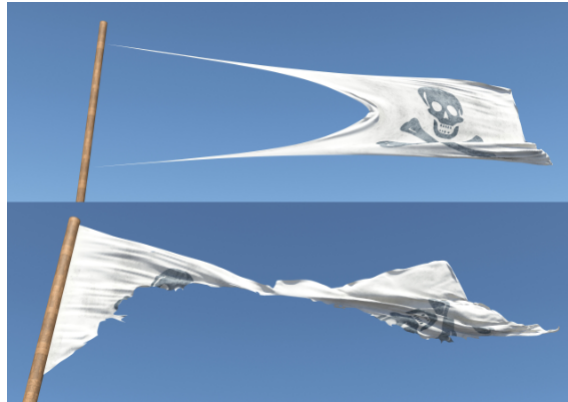


Figure 3: The simulation remaining stable in high wind speeds

In 2022, Li et al., proposed a new differentiable cloth simulation based on projective dynamics, but with dry frictional contact to simulate cloth self collision (Li, Du, Wu, Xu, & Matusik, 2022). The key difference of this work is that the simulation is differentiable, meaning gradients can be computed through backpropagation. This means that it can utilise many optimisation methods that result in a great speedup compared to non differentiable simulations. It also aims to further improve upon the physical accuracy of projective dynamics by adding dry frictional contact. The paper showcases the simulator in many different use cases to showcase the efficacy of it. One of these examples showcases the usefulness of dry frictional contact, a piece of cloth falling onto a sphere. This is a very standard test in cloth simulation. This example contains both self collision from the cloth and also external contact with the sphere. After colliding the motion was mostly from the frictional component.

Another example is a real-to-sim implementation of a flag. They used real motion of a flag blowing in the wind and tried to create a digital simulation copy. This was particularly challenging as it involved estimating what material was used and also modelling the wind condition at the time. They found it to be a good recreation of it but noted that due to the final loss function being non-zero, it was still imperfect. This is most likely due to the simplistic wind model they employed and could be improved with a more sophisticated model, such as one from a neural network.

When evaluating the implementation, they found that it successfully accommodated rich and detailed self contact, differentiability and dry frictional contact. Since it was differentiable, they were able to utilise backpropaga-

tion and observe a significant speedup when compared to other direct solvers. There are a few limitations with this model, one being that since it is based on projective dynamics, it limits the choice of material. Another significant drawback is that the solver doesn't guarantee convergence, even though it is rare for this to happen, it still results in a costly switch to a direct solver. They note that they hope to resolve this in the future.

2.6 Future Trends

Since clothing is so prevalent in daily life, the graphics and physics research communities are always striving to improve and innovate the simulation of cloth. The evolution of cloth simulation can and will take many paths. One such path can be seen recently in the works of Clegg et al., which is robot-assisted dressing (Clegg et al., 2020). In the future, robots will most likely be interacting physically with humans more, one of these areas could be robot-assisted dressing. As clothing is extremely dynamic, the robot will need accurate cloth simulations to properly assist dressing.

Another possible future trend would be cloth simulations with AI. As previously discussed in section 2.5.4, there are already examples of cloth simulations using neural networks for constraints. As machine learning and AI techniques improve, we could see more models being trained on real world clothing data and being used in more simulations.

Finally, one more possible future trend is the increasing realism of clothing simulations. As seen in section 2.5.6, projective dynamics utilised the high accuracy of continuum based methods to more accurately simulate clothing. Perhaps in the future, continuum models will improve to accurately simulate a massive range of materials and textures that all have different properties. This would impact most use cases of cloth simulation such as garment try ons, video games and more.

2.7 Conclusion

The field of cloth simulation has faced major advancements in the past two decades through a variety of approaches both traditional and novel. Both offline and real-time simulations have seen great improvements through the evolution of methods and by building upon previous works.

Offline simulation has seen advancements in the form of accuracy and attention to detail. As these simulations are not bound by frame times, they

can afford to spend much more time computing effects. This leads to simulations with incredible precision. These are typically seen in animation and film for high visual fidelity.

Real time simulations have also seen big improvements to how they are made. As the use cases for clothing simulations are so large, there have been many different methods to creating simulations, such as camera capture. This is an important step forward as it enables the capture of real life clothing which not only helps to create realistic simulations, but can also be used as data to be fed into other computational models.

Neural networks have also been a big focus for many researchers in the field due to the rapid improvement of AI techniques in recent years. These neural networks can have great predictive capabilities and room to learn off of previous data, which makes it suitable for large or detailed cloth models. Neural network cloth simulations will continue to be improved upon with models holding more data and variables, resulting in more physically accurate simulations.

Despite all of these advancements, the field continues to face hurdles in developing these simulations, such as scalability, computational efficiency and physical accuracy. The future of cloth simulations will likely be solving these problems and discovering new techniques to more accurately model cloth as it appears in the real world.

In conclusion, the literature on cloth simulation reflects a massive field, that is marked by novel and innovate approaches dedicated to improving the realism of cloth simulation. The combination of traditional methods rooted in classical physics, and the interesting techniques in computer science such as neural networks and camera capture highlights the progress of the field to date, but also opens the door to future breakthroughs that will further improve and scale cloth simulations.

3 Methodology

This section will discuss how various methods of constructing a cloth simulation were achieved inside a physics framework. It will go into depth on the design choices such as which framework to use, programming language and experiment setup. It will also cover the different algorithms used and how they compare with one another. Finally, it will discuss the additional features implemented and how they were useful in evaluating the simulation.

3.1 Environment and Framework

Before starting, a choice of which framework to implement the cloth simulation in was required. In this project, a simulation framework is just a sandbox containing the basic necessities for calculating, updating and rendering meshes that are composed of vertices and triangles. In the field of computer graphics/games development, there are a vast number of engines and physics frameworks to choose from. Some of these include: Unity, Unreal Engine, Godot, Nvidia PhysX etc. Research was done into various frameworks but eventually Unity was chosen for this project.

Unity is typically used for game development but it is also a very useful tool for building interactive simulations. It has powerful graphics capabilities for shaders and lighting which will highlight the dynamics in cloth well. It also has a massive ecosystem of resources and community support so that any problems or bugs would already be discussed online. Unity also has features that handle collisions, which was useful for implementing a level of interaction where the user can click and drag the cloth around.

3.1.1 Language Choice

Unity's base scripting language is C#, a high-level object-oriented language. C# is a managed language, meaning it will only execute while being managed by a common language runtime environment. This provides features such as memory management, garbage collection and security tools. C# is a common language used in games development but for physics simulations, C++ pulls ahead due to its high performance. C++ compiles straight to machine code which interacts much faster with the hardware it is running on.

A base script contains two functions, Start() and Update(). Start is called once at the beginning of the simulation and Update is called every frame.

Typically simulations set up all the necessary components such as meshes, colliders and variables in the Start function, and handles the main simulation loop in Update. An important detail about using Unity for physics simulations is the use of a function called FixedUpdate. Compared to the standard Update, FixedUpdate runs at a fixed time interval with a default value of 0.02 seconds, or 50 frames per second. FixedUpdate is necessary for physics simulations due to the amount of complex calculations within them. In this project, Update was only used to handle user interaction with the mouse, and to handle recordings.

Typically, Unity scripts will be solely written in C#, but through the use of dynamic link libraries (DLLs), it is possible to write an external c++ program that is used as a plugin in Unity.

Listing 1: Interfacing C++ functions with Unity

```

1 public class cppFunctions
2 {
3     [DllImport("clothsim.dll", EntryPoint = "cpp_init")]
4     public static extern void cpp_init([In] Vector3[] vertices,[In] int[] triangles, int numParticles, int ←
        numTriangles, float fixedDeltaTime, int algorithmType, int scenario, int solverIterations, [In] ←
        int[] staticParticleIndices, int numStaticParticles, int subSteps, Vector3 sphereCenter, float ←
        sphereRadius);
5
6     [DllImport("clothsim.dll", EntryPoint = "cpp_update")]
7     public static extern void cpp_update([Out] Vector3[] vertices,[In] float windStrength, [In] float ←
        stretchingStiffness, [In] float shearingStiffness, [In] int selectedParticleIndex, [In] Vector3 ←
        mouseWorldPos, [In] int stopGrabbingIndex);
8 }

```

Using this class within C#, allows the user to pass in variables from C# to C++. This allows for the sections that require excellent performance, the PBD/XPBD simulation loop, to be executed in C++. The simulation loop requires good performance because cloth dynamics require complex calculations on a lot of particles at every frame.

Variables passed this way can be specified with [In] or [Out] which help specify the direction of data flow. [In] is used for data that doesn't need to be passed back from C++ to C#, such as the initialisation variables. [Out] is used when data needs to be changed inside C++ and returned to C#, such as the vertices of the mesh. The vertices need to be passed back to C#, as Unity needs the new vertices every frame to properly render the cloth while it changes shape.

The general way this works is that the C++ dll has a cloth simulation object that is created the first time that instance of Unity runs it. It then maintains this object while Unity is open. To get the simulation ready for

the next time it is run, all the class variables are reassigned and all the class vectors are cleared.

For this project, only the simple mass spring system was implemented in C#, while all other methods were implemented in the faster C++ code. A boolean flag was used for this, if it was set to C#, it would execute code in the same script, while if it was set to C++, it would call the `cpp_init` function as seen in Listing 1.

Within the C++ application, the GLM library is also integrated. GLM is a powerful library designed for mathematics in computer graphics (G-Truc Creation, 2024). In this project, GLM is used mainly for its `vec3` class, to represent 3D vectors such as position, velocity etc. GLM also contains very useful methods for operating on these 3D vectors such as `normalize` and `length`, which are crucial for certain calculations in the `pbd` and `xpbd` simulation loops. It is a header only library so the `glm` folder was simply placed in project directory and added to necessary C++ files with `#include <glm.hpp>`.

3.2 Initialisation

Initialisation is an important part of the simulation, as it effectively determines the starting state of all objects within it. To start, a cloth mesh is needed. This is typically a flat vertical mesh, meaning it has no depth in the `z` axis. Initially, a default Unity preset mesh was used for testing. A problem quickly arose where the orientation of the mesh was wrong. This preset mesh was intended to be used as a ground or horizontal surface. When the mesh was rotated horizontally, the `y` axis became aligned horizontally instead of vertically, which disrupted the physics calculations. Consequently, it was decided to create the mesh from scratch to ensure proper alignment.

3.2.1 Mesh Creation

In Unity, an empty mesh object can be created then filled by the developer to suit their purposes. Meshes require two properties to be set, vertices and triangles. Vertices are just individual points in space, represented by a 3D coordinate. They are used to define the meshes overall structure. Triangles are geometric primitives used to represent the surface of the mesh, and are created by connecting three vertices in a sequence. Another important list is the triangle indices. these indices specify which vertices are used to create a triangle. This is necessary for creating constraints and will be discussed in

Section 3.4.1.

For this project, a mesh generator class was created and holds two functions. `GenerateVerticalMesh` and `GenerateHorizontalMesh`. Two parameters are passed to these functions, Grid size and spacing. Grid size represents how many vertices in the x and y axis, e.g. a 20x20 mesh, and spacing refers to the distance between each vertex. For most tests, a 20x20 grid is used with a spacing of 0.5. Creating the vertices is simple, a nested for loop is used and each vertex is set within. The only line within the nested loops is: `vertices[i] = new Vector3(x * spacing, y * spacing, 0);` In the code block, the outer loop iterates over the y-axis coordinates while the inner loop iterates over the x-axis, both from 0 to `gridSize`. Within the loop this line is executed to generate the coordinate at that index. The x and y coordinates of each vertex are set depending on the current position within the grid, multiplied by spacing to either increase or decrease the space between the vertices. The z coordinate is set to 0 as the cloth has no depth.

Generating triangles is a slightly more difficult. For this project, a 20 by 20 mesh will generate 2166 triangle indices, with 722 triangles. The way these triangles are generated is another nested for loop, working on 6 vertices at once and creating two triangles from them. It then moves onto the next 6 vertices. The data stored in the triangles array are the indices of the triangles.

Finally, the vertices and triangle arrays are assigned to the mesh object. Additionally, the `RecalculateNormals` function is called to calculate the normals of this mesh. Normals are necessary for lighting calculations, and they will be recalculated every `fixedUpdate`. A wireframe of this mesh can be seen in Figure 4.

3.2.2 Particle Class

One detail that is common to all techniques used in this project is the idea of each vertex being a “particle”. As mentioned in Section 2.3, vertices can be represented as particles that have various properties. Here, the particle is represented by a class that has 4 properties: *position*, *velocity*, *inverse mass* and *isStatic*. While the first three are fairly self explanatory, the last *isStatic* property determines whether that particle is fixed in space, and is a boolean. This *isStatic* variable is very useful for cloth as it allows for certain particles to be pinned, e.g. a hanging curtain or attachment points of a cape to the back of a character model.

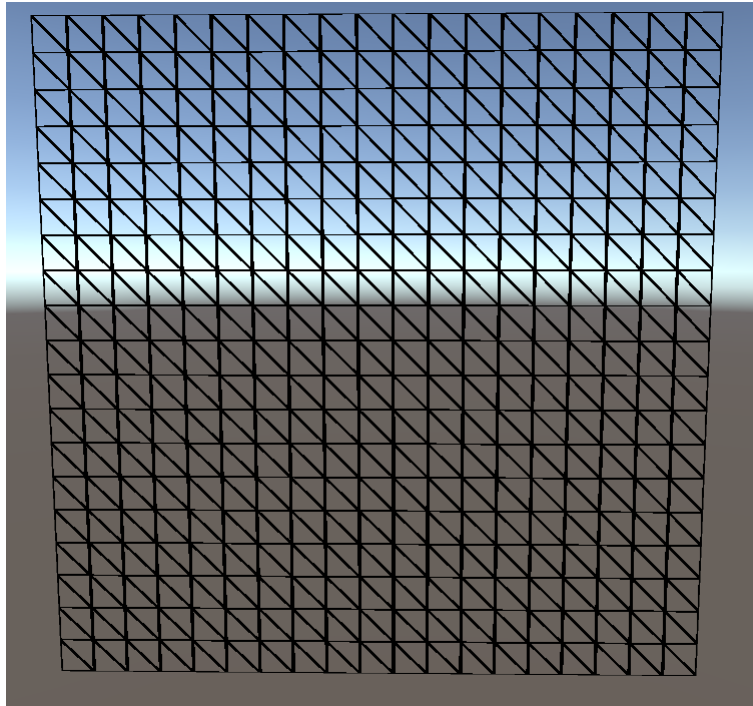


Figure 4: A wireframe of a vertical cloth mesh

One important part of initialisation is looping through all the vertices of the mesh and adding them to a particle list. In this loop, particles are assigned the position of the vertex, an initial velocity of 0, an inverse mass of 1.0 and *isStatic* set to false. Directly after this loop, the static particles are set depending on the configuration. The hanging cloth scenario has two static particles holding the top corners up. All physics calculations loop through the particle list, as it allows the important properties to be set, such as velocity and position.

One final property is required when using position based dynamics, and that is *predicted position*. Since PBD iteratively works on the predicted position during the time-step depending on external forces, an additional property is needed to store this. At the end of the time-step, the position is then updated to match the calculated predicted position.

3.3 Mass-Spring System

Now that the mesh is successfully created, the first cloth simulation method that was implemented was the mass-spring system. As discussed in Section

2.5.1, the simplest mass spring system calculates spring forces using Hooke's Law between neighbouring particles to then apply forces to these particles. Before implementing these spring forces, an integration scheme is required to modify the particles positions and velocities at each time step. There were a few options to choose from such as explicit Euler, implicit Euler and symplectic (semi-implicit) Euler, which are discussed in "An Introduction to Computer Simulation Methods" by Gould et al. (Gould, Tobochnik, & Christian, 2007). In general, explicit is simple and fast, but unstable and less accurate than others, while implicit is more computationally expensive and accurate. Semi-implicit strikes a nice balance between these two methods, giving more stability than explicit and with less computational cost than implicit. In semi-implicit integration, the particle's new velocity is calculated from external forces first and this new velocity is then used to calculate the new position. With this integration scheme implemented, the particles now fall down due to gravity. A simple directional vector was also added to the external forces to simulate wind. This vector changes direction based on a sine wave and total simulation time.

Mass-spring cloth simulations can use a variety of springs to simulate different cloth properties. The most typical are the structural springs and these link adjacent particles. Additional ones can include bend and shear springs which can be visualised in Figure 5. These additional springs can help the realism of the cloth simulation to more closely simulate the properties of real life cloth. In this project, mass-spring was not the main focus so only structural springs were implemented.

The code looped through all particles and executed an `ApplySpringForce` function where each spring is located. This meant using grid size and the loop counter. For structural springs, it can use the index and apply the spring force between `particle[index]` and `particle[index+1]` for horizontal springs. For vertical, it can be between `particle[index]` and `particle[index+gridSize]`.

For applying these forces, Hooke's law is used. This states that force exerted on the springs by the particles is proportional to the displacement of the connected particles to a rest length. In this case, the rest length is equal to the spacing variable which is the cloth mesh at rest. This force between particles due to the springs can be used to calculate a velocity change that is applied to both particles connected by the spring. The magnitude of this force can be modified with a variable known as the spring constant. This is a parameter that is uniquely tuned depending on the simulation. It effectively modifies the stiffness of the spring. High spring constants result in a very

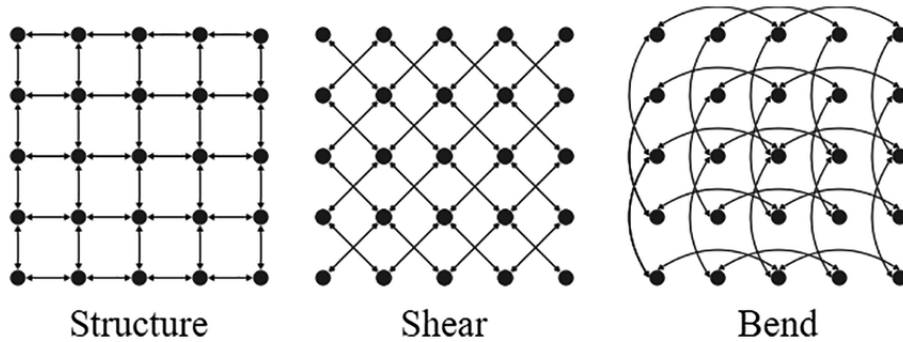


Figure 5: The types of springs typically used. Figure adapted from (Va et al., 2021).

stiff cloth, while a lower constant results in a loose one.

As mentioned before, mass-spring systems can typically be unstable with the aforementioned integration schemes. A high spring constant can exacerbate these stability problems and can cause the simulation to "explode", a term used in the field that refers to numerical instability that quickly goes out of control.

In this project, a spring constant of 1000 was used. In the C# version, increasing it higher than this it will cause rapid instability. After implementing this, the basic mass-spring system worked as intended. With two anchor points at the top left and right of the cloth, it hangs down and blows in the wind. It is to be noted that this setup with the spring constant of 1000 is still extremely loose and doesn't accurately represent any real life cloth material, which leads to the next section on the position based dynamics implementation.

The very same system was also implemented in the C++ version. This was so that the differences in performance between the two languages can be analysed. The results of these experiments will be discussed in Section 4.1.

3.4 Position Based Dynamics

With a valid simulation framework setup with mesh creation, particle vectors and the simulation loop working, the next thing to implement was position based dynamics. From this point, features were only created in the C++ version, as going back and forth between languages to implement the same things was not the best usage of time. As mentioned in Section 3.1.1, the C++ program allows variables to be passed from C# to the C++ app. This

means a cloth simulation object can be created within C++ that assigns all the variables passed through, into properties of the cloth simulation object. Some of these variables can include vertex positions, triangle indices, solver iterations etc. There are two int variables that are used in switch statements within init and update, called scenario and algorithm. These variables switch into blocks of code to change how the simulation is run, scenario determines if the cloth is a hanging vertical cloth, or if its a horizontal cloth falling on a sphere. Algorithm changes which method is being used, between mass-spring, pbd and xpbid.

The PBD simulation loop is implemented in C++ based on the description of (Müller et al., 2007), as seen in Section 2.5.6. Firstly, to handle particles the static particles that should be skipped, a simple check can be used on the *isStatic* property of that particle in the loop, skipping that particle if the property is true.

The first step of the algorithm is updating the particles velocity by utilising delta time and the external forces of the system. In this case, gravity and wind. The idea of this “for all vertices” block appears multiple times within the algorithm and can be translated to code as seen in Listing 2.

Listing 2: Updating particles velocity using external forces

```

1 for (int i = 0; i < _num_particles; i++)
2 {
3     if (!_particles[i].is_static) {
4         glm::vec3 external_forces = GRAVITY + (WIND_FORCE * wind_strength * std::sin(↵
         _total_time));
5         _particles[i].velocity += _delta_time * _particles[i].inverse_mass * external_forces;
6     }
7 }

```

Here, gravity and wind force are constants defined in the header file as `const glm::vec3 GRAVITY = glm::vec3(0.0f, -9.81f, 0.0f);` and `const glm::vec3 WIND_FORCE = glm::vec3(0.0f, 0.0f, 1.0f);` respectively. This step is very similar to the first step of symplectic Euler in the mass spring system, calculating the new velocity.

Next, the velocity was damped to 99% of its original value to simulate air friction. In the paper, the authors note that any form of damping can be used here.

The next step is to calculate the predicted position of the particle, based on the new velocity. This predicted position will then be iterated on for a specified number of times to get it closer to the goal position. This requires constraints which are key to the whole algorithm.

3.4.1 Constraints

At its core, constraints in position based dynamics are similar to springs in a mass spring system, a way of adjusting particles so that they fit a certain constraint. Position based dynamics can be used for a vast range of deformable objects and can use constraints such as volume constraints. For cloth, structural and shear constraints are used.

Generating Constraints

Initially, constraints were held in a vector of `uvec2`, a glm type that holds two unsigned integers, and these integers would be the indices of the particles that are involved in this constraint. The constraints were generated using `gridSize` in a similar way to the mass spring system within a nested for loop, which can be seen in Listing 3.

Listing 3: The inner loop for constraint generation

```
1 // Horizontal constraint
2 if (x < gridSize - 1)
3 {
4     _structural_constraints.push_back(glm::uvec2(index, index + 1));
5 }
6
7 // Vertical constraint
8 if (y < gridSize - 1)
9 {
10     _structural_constraints.push_back(glm::uvec2(index, index + gridSize));
11 }
```

This worked well for a basic PBD implementation but problems quickly arose when creating constraints on diagonals. In order to discuss the problems, it is necessary to explain constraint projection first.

Constraint Projection

Once all constraints are generated and added to a vector, they can be used within the PBD simulation loop to iteratively move the particles to attempt to satisfy all constraints in the system. A integer variable called solver iterations was added and this controlled the amount of times to loop over the list of constraints and work on them again. This number typically ranged between 10 to 30 in testing, higher numbers resulted in more accurate simulations but also increased computational cost, as it had many more calculations to do each loop.

Constraint projection is simply the act of moving particles so that they satisfy the constraint. To satisfy a constraint in a cloth simulation like this, is

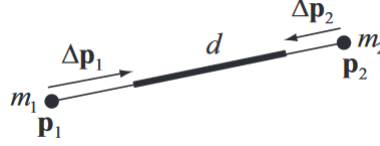


Figure 6: Projection of a constraint between two particles. Figure adapted from (Müller et al., 2007).

achieved by having a goal distance. This goal distance was set to the distance between the two particles at the start of the simulation, the rest distance. This is where the first problem with the original design appeared. Originally, constraint projection had a hardcoded rest distance set to the spacing variable discussed back in Section 3.2.1, this works fine for structural constraints, but when generating constraints in the diagonal, the rest distance of those two particles is equal to $\sqrt{r^2 + r^2}$, where r is the spacing variable. This was resolved by changing the data structure holding constraints to a vector holding a pair of `uvec2` and `float`. This float would hold the rest distance of that constraint.

To actually project these constraints involves calculating two Δp , corrections that are applied to each particle to move it towards the goal, this can be seen in Figure 6, these corrections would be weighted on the inverse masses of each particle. This is especially useful for static particles, as the inverse mass of those are set to 0. The formula for calculating these corrections turns out to be a special case of the general constraint method in the paper, and becomes:

$$\Delta p_1 = -\frac{w_1}{w_1 + w_2}(|p_1 - p_2| - d) \frac{p_1 - p_2}{|p_1 - p_2|}$$

$$\Delta p_2 = +\frac{w_2}{w_1 + w_2}(|p_1 - p_2| - d) \frac{p_1 - p_2}{|p_1 - p_2|}$$

Where w is the inverse mass, p is the predicted position and d is the rest distance. Once these corrections are calculated, they are added to the predicted position of the respective particle during the loop.

Another aspect of constraints is stiffness. In the PBD implementation, stiffness is obtained by multiplying Δp by $k \in [0...1]$. This works, but the effect of this stiffness is non-linear with multiple solver iterations. This can be fixed by calculating $k' = 1 - (1 - k)^{1/n_s}$, where n_s is the number of solver iterations. This is then used to multiply Δp .

Improved Constraint Generation

A problem with the earlier constraint generation was that it relied on the grid size variable. This means it would only work for a X by X square mesh, this is obviously not ideal, so the constraint generation needed to be reworked. One way to do this is by using the triangle data. Relying on the fact that the triangle data passed in is sorted by adjacency, we can use the indices of these to generate the constraints.

This is achieved by looping through the number of triangles, incrementing by two each time, and working on two triangles at once. The first triangle's indices can be retrieved with the index, while the second triangle's indices can be retrieved with $\text{index} + 1$. With all 6 vertices of these two triangles, it is easy to create both structural and shear constraints in this manner.

Sets of pairs of ints were created to hold temporary constraints. There were two main reasons for this approach. In C++, elements of a set have to be unique, this is to avoid creating duplicate constraints, e.g. $C(p_1, p_2)$ and $C(p_2, p_1)$. Using a function called minmax, the pair of ints can be sorted so that the lowest value is first. This is used in tandem with the property of sets to make sure each constraint is only created once. A full example is: a constraint between particle index 1 and index 20 is created as $(1, 20)$ and inserted into the set. When the loop goes to create a constraint between index 20 and index 1, minmax will turn it into $(1, 20)$ and it won't be added to the set as it already exists in there.

Once the temporary sets are created, they can be looped through and inserted into the constraints vector along with the rest length between the two particles. With this new constraint generation, any mesh can be used so long as the triangle data is sorted by adjacent triangles.

3.4.2 Updating Position and Velocity

Once the constraints have been projected for a given number of times, it is necessary to set the particles new velocity and position. The velocity can be calculated as: $v_1 = \frac{p_1 - x_1}{dt}$, where p_1 is the predicted position, x_1 is the current position and dt is delta time. After this, the particles position is simply updated to match the calculated predicted position. It is also necessary to update the positions vector that is passed back to Unity, as this will update the meshes vertex positions.

With this entire loop, the PBD implementation correctly works to simulate cloth with great performance and good accuracy.

3.5 Extended Position Based Dynamics

Now that PBD is successfully implemented, the XPBD extension can also be implemented. This was added as another algorithm type, so that it is easy to switch between them. The first major improvement that XPBD offers is the usage of substeps.

3.5.1 Substeps vs Solver Iterations

In the XPBD paper, the authors found that spending the fixed time budget of one frame is much more effective by using substeps instead of solver iterations. In essence, XPBD encapsulates the whole PBD simulation in a loop of substeps, instead of wrapping the constraint projection inside solver iterations. This means that constraints are processed only once per substep. However, multiple substeps are executed within a single simulation loop, allowing for iterative processing of constraints across the entire simulation.

After understanding XPBD's approach to simulating, it is clear that the way delta time is handled needs to be tweaked. Instead of using delta time within the loop, a new measurement of delta time substeps is calculated as $\Delta t_s = \frac{\Delta t}{n}$, where n is the number of substeps. This new variable represents the duration of each substep.

This new approach of using substeps solves the original problem with PBD, the constraint stiffness depending on time step.

3.5.2 Stiffness through a Compliance Factor

With XPBD, there is also an extension to how constraint stiffness is altered. PBD handles stiffness by multiplying the correction by a stiffness variable between 0 and 1 as discussed in Section 3.4.1. With XPBD, a compliance factor is used. Within XPBD, compliance represents the inverse of physical stiffness, meaning the constraint is infinitely stiff when compliance (α) is 0. Compliance fits into the correction equation as so:

$$\Delta p_1 = -\frac{w_1}{w_1 + w_2 + \frac{\alpha}{\Delta t^2}}(|p_1 - p_2| - d)\frac{p_1 - p_2}{|p_1 - p_2|}$$

With this extra factor, this way of applying stiffness to a constraint is much preferred over the original PBD, as it doesn't depend on time steps any more.

3.6 User Cloth interaction

An additional feature created was user interaction through the mouse. This feature would allow the user to click, hold and drag a particle around in space. When the mouse button is held, the chosen particle acts as a static particle with infinite mass, allowing the constraints to function as if this particle was pinned.

The way this is achieved is through Unity's raycasting support. If the mouse is clicked, a ray is cast from the camera in the direction of the mouse cursor. If this ray hits the collider of the cloth mesh, the exact position of this collision is calculated. Another helper function was created to find the nearest particle to this position. This is a minimisation function that loops through all particles to calculate which particle is closest to the collision point, the particle's index is then returned. Finally, this mouse position is converted from screen space to world space, with the z coordinate being the distance from camera to the cloth. The particle's index and mouse position are then passed to C++ where it is utilised in the simulation loop.

The code for user interaction is implemented within the regular Update method. This is because user interactions such as mouse clicks can happen every frame, and thus need the additional responsiveness from Update compared to FixedUpdate. If this was implemented in FixedUpdate, there could be situations where a mouse click occurs between two consecutive FixedUpdate calls, resulting in a missed input.

One additional integer is also passed through, stopGrabbingIndex. This is needed to revert the particle's properties back to normal when the mouse click is released. Two if statements that facilitate the grabbing feature can be seen in Listing 4.

Listing 4: Modifying particles from user interaction

```
1 if (stop_grabbing_index != -1)
2 {
3     _particles[stop_grabbing_index].inverse_mass = 1.0f;
4     _particles[stop_grabbing_index].is_static = false;
5 }
6 if (selected_particle_index != -1)
7 {
8     _particles[selected_particle_index].inverse_mass = 0.0f;
9     _particles[selected_particle_index].is_static = true;
10 }
```

It is necessary to set the mass as well as the static property, to allow the constraints between this held particle and other particles to function prop-

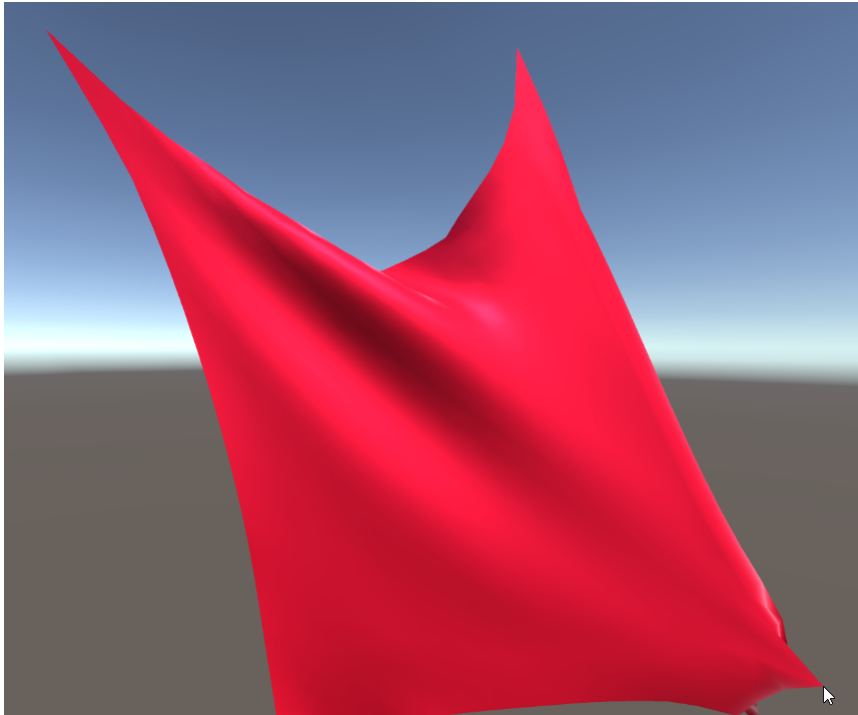


Figure 7: Hanging cloth mesh being dragged by a corner particle

erly, as the constraints are weighted based on both particles mass. Inside the PBD/XPBD loop, when calculating the predicted position, if the current particle is held, then the predicted position is just set to the mouse world position, instead of calculating it based on velocity. With this feature implemented, the user is able to click and drag any particle in the mesh, allowing the cloth to be tested for situations like folding and stretching. This can be seen in Figure 7.

3.7 Cloth and Sphere Collision

Collision was the next feature to be implemented for use in the scenario of a horizontal cloth falling on top of a static sphere. First, a simple sphere object was created within Unity using the sphere primitive. This will have two relevant properties: Sphere centre and sphere radius. There are many ways to do collision in physics simulations and the implementation depends on the scenario and usage of it. It is mentioned by the authors in the original PBD paper that position based approaches have an advantage compared to normal methods because of how easy it is to implement collision and response. They do this by creating collision constraints. With collision between cloth and a

small rigid body, two way collision is required, due to the fact that the small object could potentially fall through the cloth. In this situation, only collision between the cloth and the sphere is needed, due to the sphere being large.

The way this collision and response is handled is by checking each particle's predicted position during the PBD/XPBD loop. A vector between the position of the sphere's centre and the predicted position can be calculated. If the length of this vector is smaller than the radius of the sphere then the particle has collided with the sphere. The depth of this collision is then calculated and multiplied with the normalised vector calculated earlier. This delta can then be added to the predicted position, to move the particle outside the sphere in the direction of this vector. This can be coded very easily as seen in Listing 5.

Listing 5: Sphere collision function

```

1 void ClothSim::CollisionWithSphere()
2 {
3     for (int i = 0; i < _num_particles; i++)
4     {
5         // Calc the vector from particle to sphere centre, if its shorter than sphere radius then a ↔
6         // collision has occurred
7         glm::vec3 particle_to_centre = _particles[i].predicted_position - _sphere_centre;
8         float length = glm::length(particle_to_centre);
9
10        if (length < _sphere_radius)
11        {
12            float depth = _sphere_radius - length;
13            depth += 0.0001f;
14            glm::vec3 delta = glm::normalize(particle_to_centre) * depth;
15            _particles[i].predicted_position += delta;
16        }
17 }

```

The $0.0001f$ that is added to the depth is known as depth bias. It is used to make sure the particles aren't just moved directly onto the sphere. This helps to avoid the cloth getting stuck, as it might still be colliding on the very next frame. It also helps with z-fighting issues, this will be discussed in Section 4.3.2.

4 Results and Discussion

Now that the entire implementation is finished, it is necessary to test and experiment with variables to fully gauge the simulations effectiveness. This will mean comparing the C++ and C# implementations, discussing the two scenarios, discussing the recorder feature that was implemented and analysing the visuals of the simulation.

4.1 C++ vs C#

As discussed in Section 3.3, the mass spring system was implemented in both C++ and C#. This will allow for testing of both versions with the same setup, to check performance. Inside Unity's Update function, a quick if/else was created to sum up and average the frames over the first 10 seconds of simulation. This will be used over 5 runs of both C++ and C# to check the true average frame time for both implementations. Frame time is a common metric in real time graphics and it represents the time taken to render a frame. Before testing, it is expected that the C++ version will outperform C#, due to the efficiency of C++ and not having to deal with garbage collection in C#. This experiment will be conducted on 20x20 mesh of spacing 0.5, a 100x100 mesh of spacing 0.125 and finally, a 150x150 mesh of spacing 0.125. The results of the first experiment can be seen in Table 1.

Run #	C# frame time (ms)	C++ frame time (ms)
1	1.695	1.569
2	1.723	1.557
3	1.732	1.521
4	1.711	1.567
5	1.670	1.528
Average	1.706	1.548

Table 1: Frame time comparison between C# and C++ for a mass spring system of 20x20 particles

It can be seen here that on average, the C++ frame time is 0.158ms faster, which is a sizeable improvement. To analyse with a bigger mesh, a 100x100 is also tested with a spacing of 0.125. This second mesh will have 10,000 vertices and 19,602 triangles, compared to 400 vertices and 722 triangles of the first experiment. The result of this second experiment can be seen in

Table 2.

Run #	C# frame time (ms)	C++ frame time (ms)
1	2.296	2.024
2	2.287	2.000
3	2.265	2.003
4	2.341	2.004
5	2.347	2.002
Average	2.307	2.007

Table 2: Frame time comparison between C# and C++ for a mass spring system of 100x100 particles

With this second experiment, the time to render a frame on both versions are higher as expected, and the C++ version still outperforms the C#, this time by 0.3ms on average. It has to be noted that at higher particle size, this mass spring system implementation is extremely elastic and doesn't truly represent any real world cloth material, and with the problem of instability at higher spring constants, it is unable to simulate accurate cloth. This could potentially be due to only structural springs being implemented, and there not being enough forces to keep the particle mesh in its original shape.

A final test using a mesh of 150x150 particles and a spacing of 0.125 was performed to test the extremes of both implementations. The results of testing both implementations with this mesh can be seen in Table 3.

Run #	C# frame time (ms)	C++ frame time (ms)
1	14.294	5.342
2	14.227	5.300
3	13.459	5.325
4	13.108	5.208
5	13.626	5.241
Average	13.743	5.283

Table 3: Frame time comparison between C# and C++ for a mass spring system of 150x150 particles

With this final experiment, there was a noticeable increase in average frame time compared to the previous two experiments, yet C++ remained well ahead vs C#. On average, C++ outperformed by 8.459ms, leading to

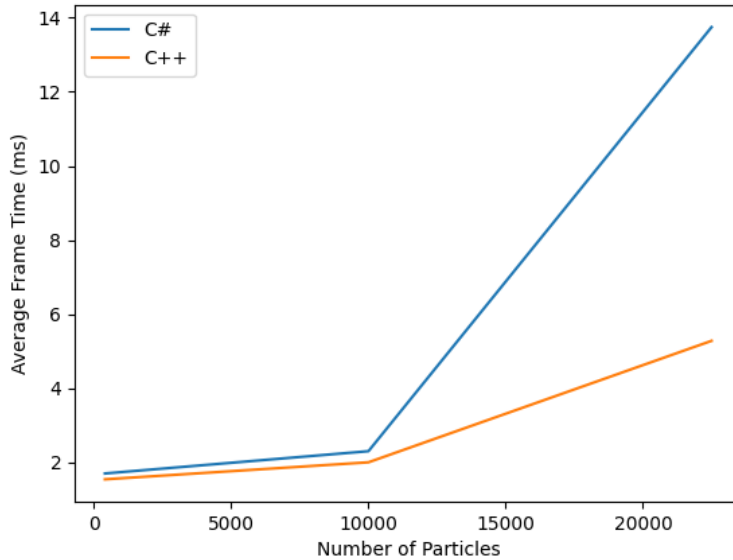


Figure 8: Average Frame Time for C# and C++ in a Mass Spring System

the conclusion that fps saved was proportional to the mesh size. This makes sense, as when the amount of calculations and vector manipulation increases, C++ will be saving more time compared to C#. For the mass spring system, any higher resolution meshes and the frame time begins to increase drastically as a result of the increased computations required.

These three experiments can be combined on a line graph to see how the number of particles affect the runtime cost in this mass spring implementation, this graph can be seen in Figure 8.

It can be seen that past a certain number of particles, the computational cost goes very high, most likely due to the significantly increased number of spring calculations to perform. The C# implementation's frame time increases drastically, while the C++ increases by a relatively small amount.

As C++ is clearly superior than C# at physics simulations, it was clear that the rest of the project was to be implemented only in C++ and to not waste development time repeating it in C#. The rest of the results will be solely resulting from the C++ code, except from features like recording videos from within Unity.

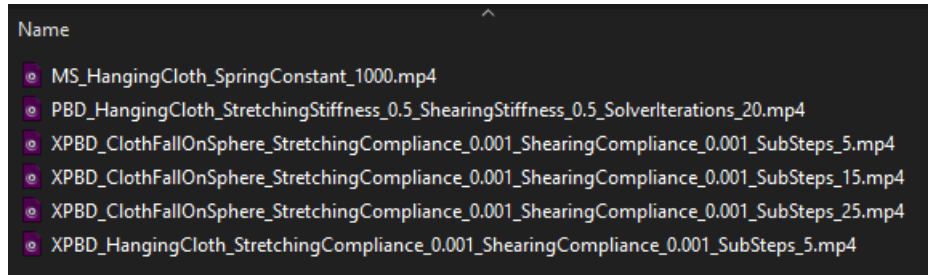


Figure 9: The folder of experiment recordings.

4.2 Recording Feature

To properly evaluate the simulations, it is necessary to record different algorithms and scenarios to be able to compare them. Unity recorder is a plugin within Unity that allows for video's and screenshots to be taken of projects. Usually it is manually used through a plugin window but it also provides an API to allow for scripts to manage recording.

With this, a mass-recording system was successfully implemented within the C# script. It uses a new class called `recordParameters` that sets variables to be tested, such as the number of PBD solver iterations, its stiffness and scenario etc. A generate filename function was also implemented that takes in a `recordParameters` object and generates a unique filename from its properties. The way this recording feature was designed allowed for lots of different experiments to be queued up and recorded in succession. In Unity's update, it checks if it is currently recording, if it isn't it takes the next pending experiment and starts it. The recording folder within the project can now hold all the experiments that are clearly identified with the filename as seen in Figure 9.

4.3 Scenarios

In this project, two distinct scenarios were implemented to test aspects of cloth simulation that are common use cases for it, such as a hanging cloth acting as things such as curtains or flags. The second scenario being a horizontal cloth falling onto a rigid sphere. This was to test how the constraints function when including collision.

4.3.1 Hanging Cloth

The first scenario is the basic hanging cloth scenario. This mesh was created vertically, so 0.0f was value for the z-axis in every coordinate when initialising. There were two main ways the cloth was pinned in testing. The first being the top two corner particles being static, this would emulate a cloth such as clothes being pinned with two pegs, or a cape. The second way was the entire top row of particles being pinned, emulating a flag. Overall, the first method was used much more in testing as it allows the constraints to be shown better, and displays interesting properties regarding the top row of particles.

Wind was also used in this scenario to apply an additional force than just gravity. Allowing the display of a system with multiple forces interacting with multiple particles. This wind was a simple vector with magnitude 1.0 in the z direction, blowing the cloth away and towards the camera. The magnitude changed between 1.0 and -1.0 using a sine function with total simulation time as the factor.

A useful property of Unity is the range property of public variables. If a range is applied above a public variable as so:

Listing 6: Unity's range feature

```
1 [Range(0f, 100f)]  
2 public float windStrength = 1.0f;
```

It will allow the user to manipulate this variable in real time with a slider. This feature is crucial in analysing different setups to display how properties such as stiffness or wind affect the simulation.

Mass-Spring System

In the mass spring system version of the hanging cloth, a variable to test the impact of is spring constant. As explain in Section 3.3, the spring constant multiplies the force applied by the springs. A higher spring constant results in a stiffer system, while a lower results in a loose one. In Figure 10, three versions of the simulation can be seen with spring constants of 500, 1000 and 1500 from left to right. The lower spring constant cloth sagging under the force of gravity while the higher spring constants hold up more. Changing this variable can help the developer tune the cloth to have different properties depending on the use case.

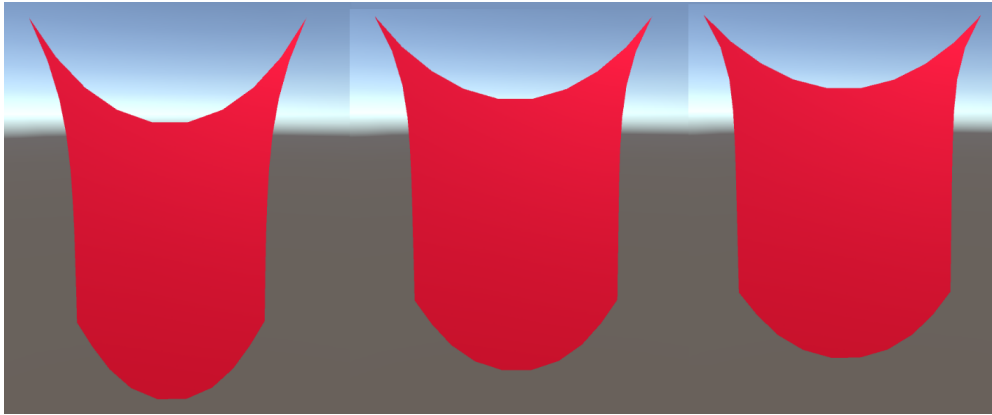


Figure 10: Three versions of the mass spring system, with spring constants of 500,1000 and 1500 left to right

Position Based Dynamics

The position based dynamics implementation within this project has a few more parameters that can be tuned and experimented with. These can include: delta time, structural stiffness, shearing stiffness and solver iterations. In the original paper, one problem was that constraint stiffness was heavily impacted by the time step and solver iterations. More specifically, the system would get more stiff as the solver iterations increased, or time step decreased. Within Unity, the fixed time step is easily modifiable in the project settings, and was normally set at 0.02s or 50 fixed updates per second. This can be then tested to verify. The only variable changing is fixed time step, the others are:

- Solver iterations = 20
- Stretching stiffness = 0.5
- Shearing stiffness = 0.5

The three time steps tested were 0.04, 0.02 and 0.01, or 25, 50 and 100 updates per second respectively. In Figure 11 it is quite apparent the severe impact that fixed time step has on the original PBD implementation. This is problematic as it requires the developer to retune all stiffness properties for different time steps, requiring much more work. This was one of the improvements that XPBD had over the original, stiffness independent of time step.

For the problem of iteration count, PBD attempts to mitigate this with the stiffness term that involves iteration count as explained in Section 3.4.1

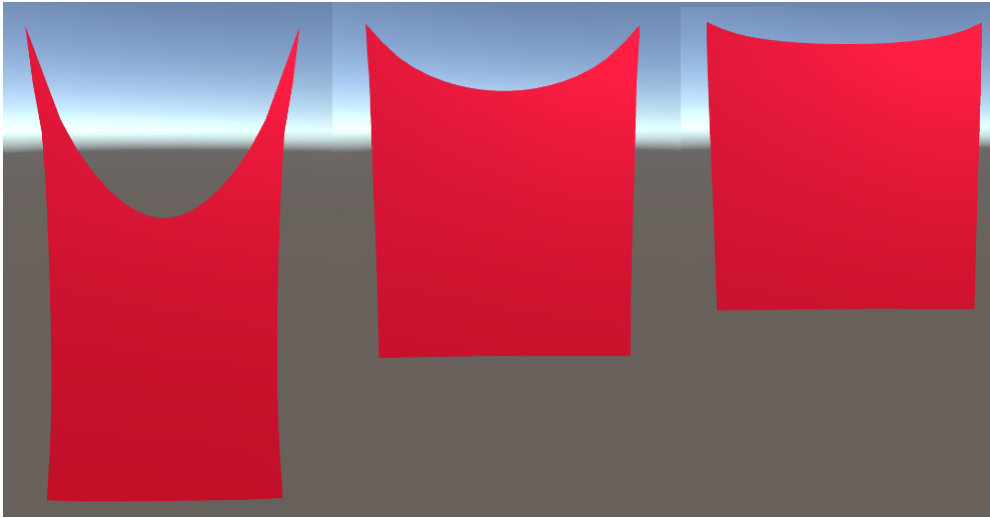


Figure 11: Testing the time step stiffness issue with original PBD, with time steps of 0.04, 0.02 and 0.01 left to right

but in the XPBD paper, the authors note that this doesn't converge to a well defined solution in the presence of multiple constraints. For this project, it successfully decouples stiffness from iteration count but for a more advanced simulation it would pose issues.

Having both structural and shear stiffness being variable allows for lots of variation in the end cloth, for example in Figure 12, the cloth on the left has a structural stiffness of 1, and a shear stiffness of 0, while the cloth on the right has both structural and shear stiffness of 1. The cloth with both stiffness set to 1 acts extremely stiff and would be suitable to represent objects such as paper or card, while the other acts more naturally like clothes or flags.

Extended Position Based Dynamics

Now, it is vital to test the hanging cloth using the extended position based dynamics method. On the whole, the overall simulation loop is extremely similar with a few improvements, substeps and stiffness compliance. Substeps were the first to be tested, the other parameters were as follows:

- Stretching compliance = 0.0005
- Shearing compliance = 0.0005
- Wind strength = 0.7

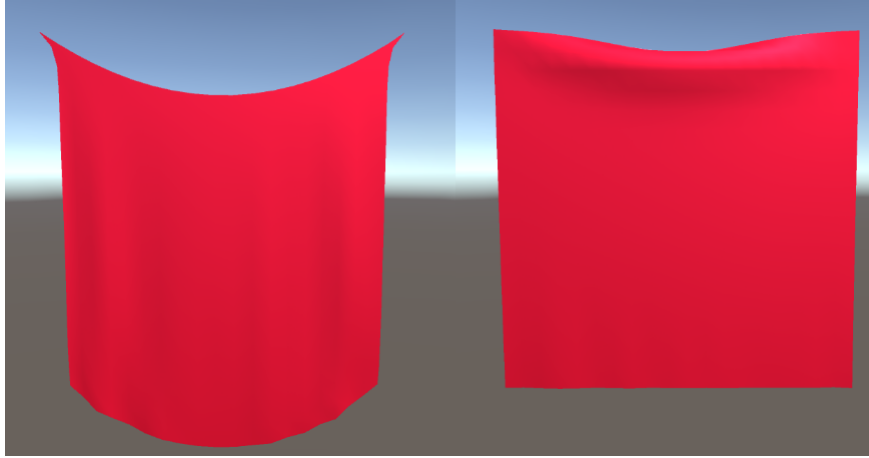


Figure 12: Cloth with different stiffness values

The substeps would be tested at 1, 10, 20, 30 and 40. This means that for every fixed update, the simulation loop would repeat for the number of substeps. It can be expected that as substeps increase, overall simulation accuracy will increase. This will come with a computational cost so the expected frame time will also be higher as substeps increase. Wind is utilised in this experiment to have an additional force on the cloth to inspect how substeps affect the constraint projection.

The recorder feature was utilised here to run these three tests, as it was easy to change substeps in the recorder class. In Listing 7, is an example of how multiple experiments were run, keeping most of the properties the same but changing substeps.

Listing 7: Utilising the recorder feature

```

1 for (int i = 0; i < 5; i++)
2 {
3     int[] subs = new int[]{1,10,20,30,40};
4     var rp = new RecordParameters
5     {
6         algorithm = 2, // XPBD
7         scenario = 0, // HangingCloth
8         xpbdsStretchingCompliance = 0.0005f,
9         xpbdsShearingCompliance = 0.0005f,
10    };
11    rp.xpbdsSubsteps = subs[i];
12    rp.filename = $"{GenerateFilename(rp)}";
13    // Add the recording settings to the pendingExperiments list
14    pendingExperiments.Add(rp);
15 }

```

When analysing these three, there are two main aspects to look at, visuals and average frame time. In Table 4, the frame time of each test is averaged over 10 seconds. It can be seen that increasing the number of substeps has a drastic effect on performance, with the 40 substeps experiment having a significantly higher frame time at 48.379ms.

Table 4: Substeps and Frame Time Data

Substeps	Frame Time (ms)
1	1.669
10	2.150
20	3.262
30	6.050
40	48.379

The visuals of the simulation are also affected. The 1 substep experiment overall looks too smooth and when moved with the mouse interaction, it has a delay before it moves. This makes sense, as the constraints are only projected once in each fixed update, so the time taken to satisfy all constraints will be considerably longer. This also means the cloth takes longer to come to rest.

This is fixed in the 20 substep version, as the constraints can be projected multiple times in one fixed update, leading to the cloth overall looking more physically realistic. It also fixes the issue of the delay before moving and it comes to rest quicker.

The 40 substeps version has taken quite the performance hit, leading to overall less appealing visuals through the higher frame time/lower fps, so the ideal substeps for this project is around 20.

Next, the time step issue from the original PBD can be tested to see if the XPBD version has fixed it. The same time step experiments used in the PBD paragraph will be used here, 0.04, 0.02 and 0.01. Before experimenting, it is expected that changing the time step will have no effect on the stiffness of the simulation, due to the new compliance factor in XPBD. The results of these experiments can be seen in Figure 13. With XPBD, the stiffness of the system now doesn't depend on the time step of the project which is a very useful improvement. Now, the developers can tune the XPBD simulation's

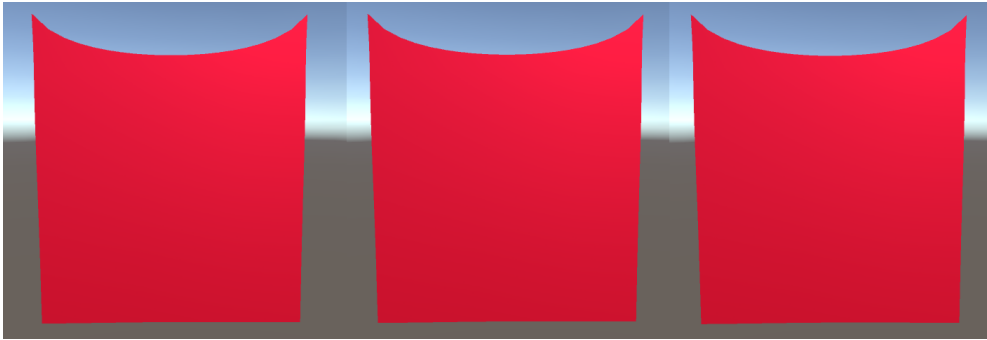


Figure 13: Time step stiffness problem resolved in XPBD

stiffness parameters to suit a wide range of time steps without having to change the parameters for different time steps.

4.3.2 Cloth falling on Sphere

The second scenario in this project is a horizontal cloth falling onto a static, rigid sphere. This scenario is made to test how the constraints function in a simulation where collision is also a factor. The horizontal cloth was generated in a similar way to the vertical cloth. When creating the vertex coordinates, the y coordinate was set to 0 instead of the z like so:

```
vertices[i] = new Vector3(x * spacing, 0, y * spacing);
```

The sphere is created in Unity, with a radius of 2.5f. The sphere centre can be obtained in C# by acquiring the transform position of the sphere game object, these two variables are then passed to C++ to be used in the collision code discussed in Section 3.7.

Initially, there was an issue where the sphere object could be seen through the cloth when they were colliding. This is a known issue in computer graphics called stitching or z-fighting. It occurs when two objects within a scene have very similar distances to the camera, which causes issues when deciding what object to render first. This problem can be visualised in Figure 14.

To address this issue, a novel approach was implemented in this project. In the cloth shader, an additional rendering pass was used alongside the command “ZTest Always”. This command specifies the depth test function for determining if a pixel should be drawn or not. By assigning “Always” to it ensured that the cloth will always be rendered on top of other objects, regardless of position.



Figure 14: Z-fighting issue when rendering two colliding objects

However, this alone wouldn't be enough to solve the issue, as the cloth would continue to be rendered on top of the sphere, even when it falls behind it. To overcome this challenge, the shader used for the sphere was modified to a transparent one. This alteration effectively transformed the appearance of the sphere into glass-like, allowing the cloth to be rendered behind it without appearing out of place. The result of this approach can be seen in Figure 15.

With this implementation, the sphere successfully collides with the sphere

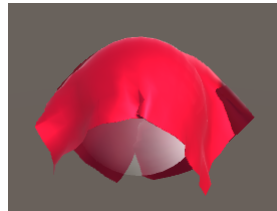


Figure 15: The glass sphere approach to solve z-fighting

and reacts in a physically plausible way, sliding off the sphere. With friction, the cloth would most likely stay on top of the sphere, but it was not implemented in this project. The way the sphere interacts with the cloth using such simple collision code, showcases the effectiveness of XPBD's constraints in simulating realistic cloth dynamics.

4.4 Discussion

With these experiments conducted, the overall effectiveness of the various cloth simulation approaches can be discussed. The first and most simple approach, the mass spring system using symplectic Euler integration was simple to implement and yielded decent results for a small grid size. It unfortunately has the instability from this type of integration and thus cannot handle rapid change in the system or it is prone to exploding. As the only

springs implemented were structural springs, it is overall very elastic and not representative of real life cloth material. One positive about the mass spring system is the ease of implementation, as it is very intuitive to treat the connections between particles as springs, which allows the use of Hooke's law to calculate resultant forces.

As this was the easiest method to implement, it was perfect to use as the comparison between C# and C++, as it was simple enough to implement in both languages. Using this test, it was found that C++ performed better than C# in every test. This is due to C++'s greater control over memory management and overall less overhead compared to C#. As discussed in Section 3.1.1, C# requires a common language runtime to execute, and also performs garbage collection. Both of these will introduce significant overheads when running code, thus performing much worse than C++ in projects such as cloth simulation, where there are a great number of calculations required.

One improvement to the mass spring system that could be introduced would be a more advanced integration method, such as Runge-Kutta or Verlet. Runge-Kutta is a higher order method that is multi-stage, meaning it performs many more calculations in order to obtain more accurate results with lower error. This results in a more accurate simulation but with a higher computational cost. The most commonly used Runge-Kutta method, RK4, involves 4 stages of calculation. Verlet integration is a commonly used second order integration method that provides good numerical stability over explicit Euler at little additional computational cost (Gould et al., 2007).

Another improvement of this mass spring system would be to implement all the additional springs seen in Figure 5. This would help with the over-elastic issue by applying more spring forces to the particles, helping the mesh to stay in a more rigid shape.

Once the original position based dynamics method was implemented it was immediately a clear improvement upon the mass spring system. Since position based methods are unconditionally stable, the simulation no longer had the chance to explode, and allowed for the testing of extreme wind forces to see how the constraints would react to massive forces, the cloth always returned to a normal shape after such forces, showcasing the robustness of the method. Implementing stiffness into PBD was simple as well, and it allowed for the cloth's visuals to be changed in real time through the Unity editor. The issue of stiffness coupled with time step was evident during testing, as

even a small change in fixed time step resulted in a massive change in stiffness. Which was one of the motivations that the authors of PBD had for creating XPBD.

The XPBD implementation was mostly derived from the PBD code, so it did not need to be recreated from scratch. The stiffness needed to be reworked to compliance which was relatively simple, also a new variable was created that denoted delta time substeps and was used in replacement for delta time. Overall, XPBD performs similarly to PBD but with the added benefits of greater control over stiffness, since the compliance factor just needs to be more than 0, instead of a fixed 0 to 1 range in PBD. It successfully fixed the time step stiffness interaction and was confirmed through testing multiple time steps. The number of substeps can be varied depending on the use case of that cloth, e.g. a prominent object within a game could benefit from the increased accuracy of more substeps, and a small background object could use smaller substeps to reduce computational cost.

The sphere scenario was also useful to see how simple collision code could create a realistic interaction between two objects through the use of XPBD, demonstrating the power of constraints. This collision code would have to be improved upon if it was to be used in a different setting, as the depth test solution wouldn't be suitable for all objects.

Overall, all 3 methods proved useful in comparing how cloth simulations are designed and created, and the experiments provided useful data on the computational cost of different parameters such as amount of particles, substeps, time step etc.

5 Reflection

This project was challenging and interesting to work on throughout the semester. It allowed me to explore more advanced parts of real time physics simulations and even some computer graphics techniques through shaders. Initially, I struggled to decide which part of cloth simulation to explore in the honours project, but through research done in the first semester while writing the literature review, I decided to focus on the implementation of various methods within a physics framework, as I much prefer writing code and seeing the visual difference than just working on the maths and physics. Initially, there was a learning curve to using Unity and C#, as I hadn't used them much in the past, but through tutorials and guides online, I quickly grasped the main functions needed to implement this project. In hindsight, I should have done this over the break between semesters, as it would've allowed me to dive straight into implementing the methods in the first weeks, instead of getting everything set up.

The hardest part of this project was effectively translating the algorithm within the papers into code, as it is sometimes not clear how to link the two. The main author of PBD/XPBD, Matthias Müller, has talks and videos online discussing the methods and they proved very useful in how to think about how these methods actually work in a more hands on way, instead of just discussions within a paper.

Referring to the initial project overview, Appendix A, the original aim of the project was to implement extended position based dynamics within a physics framework and effectively analyse the simulation through experiments. Overall, I feel this was achieved to a good standard. It successfully utilised the method to implement two scenarios of cloth simulation that worked well. Implementing a C++ dll and linking it to Unity was a great idea and proved very useful in testing to showcase why C++ is the preferred language for physics simulations. The downside to this implementation is that it is more of a stand-alone project, and that it wasn't utilised in an actual game or animation. During meetings it was suggested that I explore a way of using my implementation on a game characters outfit to see how it handles that scenario, but this wasn't achieved due to time limitations.

When comparing this implementation to other works, I felt my version was to a reasonable standard. The more advanced versions online that include things like self collision and additional constraints surpassed my version, but with likely more work devoted to it. A potential use case for this

project could be in education. It is typical in academic papers to dive into the theories and methodologies behind many algorithms, but commonly lack detail about the ways to implement these algorithms in code. With tweaks, this project could be used to showcase how these methods are utilised in a physics framework.

Although PBD and XPBD were explored to a high degree in this project, there is much room for improvements and additional features to be implemented. If this project was to be revisited, the first thing to be implemented would be the character cloth combination as discussed earlier, or a similar scenario like a cape on the back of a moving character.

One idea that was briefly considered during the project was self collision. This would allow the cloth to interact with itself, providing more realistic visuals. It was going to be the next thing I implemented but I ran out of time, perhaps with better planning I would've been able to.

Another potential avenue for future work would be exploring a GPU implementation of this project. Cloth simulation is a very commonly parallelised problem and it would be interesting to see how I could use my knowledge from the concurrent and parallel systems module to attempt this. The biggest benefit from GPU programming is the massive increase in computational power.

Overall, I think this project was on the whole, a success. The project aims were achieved, and while there could've been an additional scenario with better planning, I think the base PBD/XPBD was implemented to a good standard. I learned a lot about real time simulations which can be applied to many other types of simulations and other physics based animations.

6 Conclusion

In conclusion, this project successfully implemented XPBD and other cloth simulation methods within a physics framework. Through experimentation, it was found that XPBD is a very effective method in accurately simulating complex cloth dynamics, while also keeping computational cost low. The mass-spring system also allowed the two programming languages C# and C++ to be compared in the context of a physics simulation. In this case, C++ came out ahead in every test. This is due to all the extra overhead that C# has, slowing down the many number of calculations required each time step, while also requiring a common language runtime environment. This is in contrast to C++ which compiles straight to machine code that will interact with the hardware much faster.

When comparing mass-spring to the position based methods, it was clear that mass-spring performed worse on a number of aspects. The instability of using symplectic Euler integration combined with mass-spring often caused the simulation to explode at high stiffness, and thus never really was able to simulate a realistic cloth. PBD and XPBD remain unconditionally stable, and this was proven by utilising both the wind force and the user interaction to test the constraints when extreme forces were applied. The stiffness was easily controllable too, through the use of Unity public ranges, they were modifiable in real time. XPBD successfully improved upon PBD by fixing the stiffness issue and the overall simulation performed better through the use of substeps.

The original aims of the initial project overview were met, which was to implement XPBD within a framework and analyse its effectiveness through testing. Extra features such as collision, user interaction and recording were also implemented to help the evaluation. The project would've benefited from an additional scenario showcasing how the method performs on clothing, but this wasn't implemented due to time constraints.

Overall, this project was a success, as it showcased the way this cloth simulation method was implemented in a framework, and allowed for various experiments to be conducted to analyse the efficiency of XPBD in simulating cloth dynamics.

References

- Baraff, D., & Witkin, A. (1998). Large steps in cloth simulation. In *Proceedings of the 25th annual conference on computer graphics and interactive techniques* (p. 43–54). New York, NY, USA: Association for Computing Machinery. Retrieved from <https://doi.org/10.1145/280814.280821> doi: 10.1145/280814.280821
- Bender, J., Müller, M., Otaduy, M. A., Teschner, M., & Macklin, M. (2014). A survey on position-based simulation methods in computer graphics. In *Computer graphics forum* (Vol. 33, pp. 228–251).
- Bender, J., Weber, D., & Diziol, R. (2013). Fast and stable cloth simulation based on multi-resolution shape matching. *Computers and Graphics*, 37(8), 945–954. Retrieved from <https://www.sciencedirect.com/science/article/pii/S0097849313001283> doi: <https://doi.org/10.1016/j.cag.2013.08.003>
- Bertiche, H., Madadi, M., & Escalera, S. (2021). *Pbns: Physically based neural simulator for unsupervised garment pose space deformation*.
- Bertiche, H., Madadi, M., & Escalera, S. (2022, nov). Neural cloth simulation. *ACM Trans. Graph.*, 41(6). Retrieved from <https://doi.org/10.1145/3550454.3555491> doi: 10.1145/3550454.3555491
- Bouaziz, S., Martin, S., Liu, T., Kavan, L., & Pauly, M. (2014, jul). Projective dynamics: fusing constraint projections for fast simulation. *ACM Trans. Graph.*, 33(4). Retrieved from <https://doi.org/10.1145/2601097.2601116> doi: 10.1145/2601097.2601116
- Breen, D. E., House, D. H., & Getto, P. H. (1992). A physically-based particle model of woven cloth. *The Visual Computer*, 8, 264–277.
- Carignan, M., Yang, Y., Thalmann, N. M., & Thalmann, D. (1992, jul). Dressing animated synthetic actors with complex deformable clothes. *SIGGRAPH Comput. Graph.*, 26(2), 99–104. Retrieved from <https://doi.org/10.1145/142920.134017> doi: 10.1145/142920.134017
- Clegg, A., Erickson, Z., Grady, P., Turk, G., Kemp, C., & Liu, K. (2020, 02). Learning to collaborate from simulation for robot-assisted dressing. *IEEE Robotics and Automation Letters*, PP, 1–1. doi: 10.1109/LRA.2020.2972852
- Cutler, L. D., Gershbein, R., Wang, X. C., Curtis, C., Maignet, E., Prasso, L., & Farson, P. (2005). An art-directed wrinkle sys-

- tem for cg character clothing. In *Proceedings of the 2005 acm siggraph/eurographics symposium on computer animation* (p. 117–125). New York, NY, USA: Association for Computing Machinery. Retrieved from <https://doi.org/10.1145/1073368.1073384> doi: 10.1145/1073368.1073384
- Etzmuß, O., Keckeisen, M., & Straßer, W. (2003). A fast finite element solution for cloth modelling. In *11th pacific conference on computer graphics and applications, 2003. proceedings.* (pp. 244–251).
- G-Truc Creation. (2024). *GLM - opengl mathematics*. <https://github.com/g-truc/glm>.
- Gould, H., Tobochnik, J., & Christian, W. (2007). *An introduction to computer simulation methods* (3rd ed.). Addison-Wesley.
- Jakobsen, T. (2001, 01). Advanced character physics. In *Game Developers Conference Proceedings*.
- Kang, Y.-M., & Cho, C.-S. (2012). Photorealistic cloth in real-time applications. *Computer Animation and Virtual Worlds*, 23(3-4), 253–265.
- Kim, D., Koh, W., Narain, R., Fatahalian, K., Treuille, A., & O'Brien, J. F. (2013). Near-exhaustive precomputation of secondary cloth effects. *ACM Transactions on Graphics (TOG)*, 32(4), 1–8.
- Kim, T. (2020). A finite element formulation of baraff-witkin cloth. *Computer Graphics Forum*, 39(8), 171–179. Retrieved from <https://onlinelibrary.wiley.com/doi/abs/10.1111/cgf.14111> doi: <https://doi.org/10.1111/cgf.14111>
- Kim, T.-Y., Chentanez, N., & Müller-Fischer, M. (2012). Long Range Attachments - A Method to Simulate Inextensible Clothing in Computer Games. In J. Lee & P. Kry (Eds.), *Eurographics/ acm siggraph symposium on computer animation*. The Eurographics Association. doi: 10.2312/SCA/SCA12/305-310
- Li, Y., Du, T., Wu, K., Xu, J., & Matusik, W. (2022, oct). Diffcloth: Differentiable cloth simulation with dry frictional contact. *ACM Trans. Graph.*, 42(1). Retrieved from <https://doi.org/10.1145/3527660> doi: 10.1145/3527660
- Macklin, M., Müller, M., & Chentanez, N. (2016). Xpbd: position-based simulation of compliant constrained dynamics. In *Proceedings of the 9th international conference on motion in games* (pp. 49–54).
- Müller, M., Heidelberger, B., Hennix, M., & Ratcliff, J. (2007). Position based dynamics. *Journal of Visual Communication and Image Representation*, 18(2), 109–118.
- Müller, M., Heidelberger, B., Teschner, M., & Gross, M. (2005, jul). Meshless deformations based on shape matching. *ACM Trans. Graph.*, 24(3), 471–478. Retrieved

- from <https://doi.org/10.1145/1073204.1073216> doi:
10.1145/1073204.1073216
- Narain, R., Overby, M., & Brown, G. E. (2016). Admm projective dynamics: fast simulation of general constitutive models. In *Proceedings of the acm siggraph/eurographics symposium on computer animation* (p. 21–28). Goslar, DEU: Eurographics Association.
- Oh, Y. J., Lee, T. M., & Lee, I.-K. (2018). Hierarchical cloth simulation using deep neural networks. In *Proceedings of computer graphics international 2018* (p. 139–146). New York, NY, USA: Association for Computing Machinery. Retrieved from <https://doi.org/10.1145/3208159.3208162> doi: 10.1145/3208159.3208162
- Provot, X. (1995). Deformation constraints in a mass-spring model to describe rigid cloth behaviour. In *Graphics interface* (pp. 147–147).
- Selle, A., Su, J., Irving, G., & Fedkiw, R. (2009). Robust high-resolution cloth using parallelism, history-based collisions, and accurate friction. *IEEE Transactions on Visualization and Computer Graphics*, 15(2), 339–350. doi: 10.1109/TVCG.2008.79
- Stumpp, T., Spillmann, J., Becker, M., & Teschner, M. (2008, 01). A geometric deformation model for stable cloth simulation. In (p. 39–46). doi: 10.2312/PE/vriphys/vriphys08/039-046
- Terzopoulos, D., Platt, J., Barr, A., & Fleischer, K. (1987). Elastically deformable models. In *Proceedings of the 14th annual conference on computer graphics and interactive techniques* (pp. 205–214).
- Va, H., Choi, M.-H., & Hong, M. (2021, 10). Parallel cloth simulation using opengl shading language. *Computer Systems Science and Engineering*, 1, 427–443. doi: 10.32604/csse.2022.020685
- Vassilev, T. I. (2017). Mass-spring cloth simulation with shape matching. In *Proceedings of the 18th international conference on computer systems and technologies* (p. 257–264). New York, NY, USA: Association for Computing Machinery. Retrieved from <https://doi.org/10.1145/3134302.3134332> doi: 10.1145/3134302.3134332
- Wang, H., O’Brien, J. F., & Ramamoorthi, R. (2011, jul). Data-driven elastic models for cloth: Modeling and measurement. *ACM Trans. Graph.*, 30(4). Retrieved from <https://doi.org/10.1145/2010324.1964966> doi: 10.1145/2010324.1964966
- Wang, K., Zhang, G., Cong, S., & Yang, J. (2023, June). Clothed human performance capture with a double-layer neural radiance fields. In *Proceedings of the ieee/cvf conference on computer vision and pattern recognition (cvpr)* (p. 21098–21107).

Weil, J. (1986). The synthesis of cloth objects. , *20*(4).

Yu, T., Zheng, Z., Guo, K., Zhao, J., Dai, Q., Li, H., . . . Liu, Y. (2018). *Doublefusion: Real-time capture of human performances with inner body shapes from a single depth sensor*.

Yu, T., Zheng, Z., Zhong, Y., Zhao, J., Dai, Q., Pons-Moll, G., & Liu, Y. (2019, June). Simulcap : Single-view human performance capture with cloth simulation. In *Proceedings of the iee/cvf conference on computer vision and pattern recognition (cvpr)*.

Appendices

A Project Overview

Matthew Lenathen

40506678

Initial Project Overview

SOC10101 Honours Project (40 Credits)

Title of Project: Cloth Simulation

Overview of Project Content and Milestones

In games development, well-constructed cloth physics can be vital in adding to a game's realism. This project will be about implementing extended position-based dynamics (XPBD) within a physics framework to simulate cloth. XPBD is an extension to a well-known technique called position-based dynamics (PBD). PBD uses position constraints to iteratively solve the positions of particles within a simulation. XPBD improves upon the accuracy and stiffness problems of the method by having the stiffness depend on the number of iterations. It can also improve upon the positional errors by shortening the time step.

This simulation will be used to analyse and evaluate different configurations of cloth, to discuss the effectiveness and value of this simulating technique.

In terms of milestones, the first goal will be the literature review, discussing areas such as: cloth simulation for film, real-time cloth simulation and other techniques, e.g., motion capture. The next milestone will be implementing the original position-based dynamics within a physics simulation framework. Next, the extended position-based dynamics will be implemented. This implementation will then be used for analysis, potentially with different cloth materials and configs to see where this technique is best suited for, and where it falls short.

If these milestones end up being simpler than initially thought, there is room to explore CPU vs GPU simulations using this technique.

The Main Deliverable(s):

The main deliverable is an implementation of extended position-based dynamics within a physics framework. The current plan is to use C++ as it is very common in physics due to its great performance and potential for optimisation. The framework will most likely be Unity, which is C#, but mainly for its visualisations, the actual physics simulation code will be in C++. This will be done by compiling the C++ code to a .dll file, then used by Unity.

The Target Audience for the Deliverable(s):

The target audience would be game developers and game/physics engine developers, as it hopefully will be useful to them in testing.

The Work to be Undertaken:

Firstly, cloth simulation in various fields will be investigated and discussed within the literature review. The main bulk of the work will be implementing XPBD within a chosen framework. It will then be used to analyse things such as performance, realism etc. The simulation can also be evaluated against other implementations to compare findings.

Additional Information / Knowledge Required:

For this project, I will need to improve my current knowledge of programming physics simulations. I have previously worked on a mass-spring cloth simulation in a previous module: Physics-based

Matthew Lenathen

40506678

animations. The knowledge gained in this module will be helpful in understanding further methods and techniques in the field.

Also, as the framework will most likely be new software to me, I will need to experiment and get to grips with that, to successfully implement this project.

Information Sources that Provide a Context for the Project:

For this project, there is a lot of information related to the topic in papers published by Matthias Müller, as he is one of the co-authors of both PBD and XPBD.

References

Macklin, M. (2016, September 15). *XPBD (submission video)*. Retrieved from Youtube: <https://www.youtube.com/watch?v=jrvJFzrF3kg>

Matthias Müller, B. H. (2006). Position Based Dynamics. *Virtual Reality Interactions and Physical Simulations (VRIPhys) 2006*.

Miles Macklin, M. M. (2016). XPBD: Position-Based Simulation of Compliant Constrained Dynamics. *MiG '16: Motion In Games* (pp. 49-54). Burlingame California: ACM.

Müller, M. (2023). *Publications*. Retrieved from Matthias Research: <https://matthias-research.github.io/pages/publications/publications.html>

The Importance of the Project:

As most 3D games in the field use some sort of cloth physics, this project is very relevant to modern games development today, and since performance is a vital aspect of game development, every bit of optimisation with these techniques can be instrumental in helping a game succeed.

As for the novelty aspect, while it is true there are many different implementations of XPBD online, I plan to test a wide range of simulations with different configurations to see how each aspect affects the overall performance. For example, a 50 by 50 cloth with just bending constraints vs a 500 by 500. Hopefully with these experiments, I can conclude what has the most impact on simulations.

The Key Challenge(s) to be Overcome:

I anticipate the main challenge to be properly understanding the maths involved in XPBD, while also being able to program the expected behaviour in C++, I will most likely have to devote a lot of time to this. Another challenge will be how to efficiently use the chosen framework, in terms of visualising the cloth simulation.

B Second Formal Review Output

SOC10101 Honours Project (40 Credits)

Week 9 Report

Student Name: Matthew Lenathen

Supervisor: Dr KONIARIS Babis

Second Marker: Dr Md Zia Ullah

Date of Meeting: 17/11/2023

Can the student provide evidence of attending supervision meetings by means of project diary sheets or other equivalent mechanism? **yes**

If not, please comment on any reasons presented

Please comment on the progress made so far

The student made good progress on the literature review chapter of the dissertation. The student has not made any implementation and simulation. Some concrete plans were made.

Is the progress satisfactory? **yes**

Can the student articulate their aims and objectives? **yes**

If yes then please comment on them, otherwise write down your suggestions.

The student was able to provide clear aims and objectives of the project and describe how the aims will be addressed. The aim is to experiment with some existing cloth simulation methods which are applicable in game design.

* Please circle one answer; if **no** is circled then this **must** be amplified in the space provided

Does the student have a plan of work? **yes** **no***

If yes then please comment on that plan otherwise write down your suggestions.

The student has some concrete plans of work.

Does the student know how they are going to evaluate their work? **yes**

If yes then please comment otherwise write down your suggestions.

The student was able to explain the evaluation procedures. Frame per second is one of them. The student was suggested to find another metric to evaluate the quality of the simulated frame.

Any other recommendations as to the future direction of the project

The project is going well since the student has made significant progress with the literature review. The student is a bit behind the implementation and simulation of the project. The student was suggested to find the relevant simulation framework, start simulation programs. It was also suggested to go deeper in understanding the state-of-the-art cloth simulation techniques in game design.

Signatures:

Supervisor: Babis Koniaris

Second Marker: Md Zia Ullah

Student: Matthew Lenathen

The student should submit a copy of this form to Moodle immediately after the review meeting; A copy should also appear as an appendix in the final dissertation.

* Please circle one answer; if **no** is circled then this **must** be amplified in the space provided

C Diary Sheets

Meeting Notes

Meeting 1 - 20/09/2023

- Discussed many points relating to the scope of the project such as:
- It will be a development based project
- It's not necessary to create stuff entirely from scratch, can use templates, libraries, engines but can also add stuff and compare to other things people have done.
- The first steps is a lot of reading to narrow down the topic area, see what people have done recently in the field.
- Structure to diss = 5 sections
 - Intro
 - General overview
 - Little summary of contents
 - Literature review
 - Summary of literature
 - Start off general and focus in on topic question by end
 - Reflect on your own work
 - Methodology
 - This section includes all the work I will do
 - Stuff like algorithms, simulations, methods, theory, equations etc
 - Make sure that whatever i did is repeatable by someone reading it
 - Results
 - In this section can e.g. use parameters and record results with graphs, tables etc. discuss and compare what i found to what other people found, is it similar, is it different, and discuss why.
 - Conclusion
 - Give the reader a memorable takeaway of the paper, what new things i found, results.
 - Reflect on the topic question and whether i answered it well.
- Latex is very useful for physics equations, will probably use it, can use zotero to export .bib files that are useful
- Google scholar for things and can import to zotero
- Read more papers and build up a database of relevant papers
- Check out siggraph, gpugems, shaderX, gpu pro for potential things
- Try to narrow down topic ideas
- Be prepared to talk about the things i read and found interesting/hard/confusing to get more knowledge

Meeting 2 - 27/09/2023

- Discussed what I had researched regarding shape matching and skinning. Decided that it looked a bit too maths/physics heavy and that I wanted to focus on programming.

- Decided that i'd do research into what's the current methods regarding cloth in game development, and that a potential project could be on comparing different methods.
- Check whats state of the art in games right now, regarding cloth.
- Check alternative methods and compare them
- Check game engines to see what they can do, also if people have made plugins that have modifiable implementations

Meeting 3 - 04/10/2023

- Discussed what I found regarding cloth in games, talked about what I would implement it in.
- Discussed the project being about implementing extended position based dynamics, have to look at a language/framework that hasn't been explored yet
- Research into various physics simulation frameworks to see which would be a good fit

Meeting 4 - 11/10/2023

- Discussed a few frameworks that i researched and decided unity would be a good fit
- Asked about the IPO and contents, doesn't have to be set in stone at this point.
- Regarding literature review, asked about initial chapters and got an idea, needs further discussion next meeting after more research
- Read more literature and think more about topics/sections for the literature review
- Finish off IPO and upload it

Meeting 5 - 18/10/2023

- Gave my initial lit review topic plans and asked Babis' opinion on them, generally fine, reshuffling of a few topics to keep the flow nice.
- Don't have a dedicated optimisation section because all papers will do it, can mention it in another section
- Babis told me of a nice way to find critical evaluations, check the papers citations and compare the work to the previous papers work.
- State of the art papers have lots more information
- About figures, not necessary in lit review, but can include some if needed
- The week 9 lit review deadline isnt fixed can move it ahead a week, two weeks might be pushing it,
- Start draft of lit review to get feedback as soon as possible.

Meeting 6 - 25/10/2023

- Emailed the start of my lit review, have intro, history and a little bit on underlying physics to talk about during the meeting.

- History of cloth section is a good example of what the markers want to see in literature review, discussion and linking of papers
- The underlying physics section is a bit out of place, cause it explains stuff that eventually PBD doesn't even use (integration techniques). This can be moved down to the mass spring sections
- Start with real time methods, can link 2.7.1 and 2.7.2 by common math
- mention PBD in 2.7.1 for the future section
- Pbd and xpbD should be under 2.7 (2.7.4)

Meeting 7 - 03/11/2023

- calculating implicit euler -> expensive
- continuum section title is too general, need to clarify.
- offline section quite bare need more papers.
- has there been convergence? in technology, can speak about that
- don't forget to critically evaluate references
- make sure to speak about the drawbacks and good way to critically link papers.
- can email any time with changes
- schedule meeting for 15th november, email him "how many days do you need it in advance"
- try to do 2:30 meeting wednesday
- siggraph -> not focused on real time, find them there
 - kesen real time rendering
 - focus on simulation

Meeting 8 - 08/11/2023

- Decided on the meeting time with Zia, would send an email after the meeting to see if he is free.
- Babis told me about latex labelling and how it's used, and rewrote parts where I didn't use it.
- Don't always need to write a page on a specific paper, can bundle in more papers and link them
- Start the PBD section with the original paper and talk about the maths.
- Babis linked a STAR paper by Matthias that I can use

Meeting 9 - 15/11/2023

Not much this meeting, basically just me writing more sections of the literature review

- Fix the precomputing sections title, too vague
- Say "the authors" because et al needs a citation nearby.
- Prep for second marker meeting

Honours Project Interim Meeting - 17/11/2023

Met with Babis and Zia to discuss the project so far. Zia asked me lots of questions such as:

- explaining cloth representation (triangles/particles etc)
- Ways to evaluate it (frame time, realism etc)
- If generative AI can do this (it cannot, physics too complicated for it rn)

Zia would then write the word doc on how it's progressing which i received and uploaded to moodle.

Meeting 10 - 22/11/2023

Meeting was skipped as I was focussing on the other modules courseworks

Meeting 11 - 29/11/2023

- Continuum stops a bit at 2011, try to get more recent papers
- Talk about performance and pros/cons, compare it to the performance at the time
- Dont use the word exciting, try things like interesting
- Get more neural network papers and link them in
- Finish literature review
- Mention cpu and gpu implementations for real time
- Delete alternative methods section and make them into their own sections, more papers too
- Try to make a shape matching section and Babis linked a paper on it.

Meeting 12 - 06/12/2023

- Babis recommended for me to get some figures for sections such as shape matching as it can be quite hard to visualise without them.
- Next step is finish literature review
- Was recommended to think about what I can evaluate and what different scenarios i will do in the simulation (e.g. draping cloth, cloth falling on top of sphere etc).
- Last meeting before the break
- Need to send email before next semester starts to sort out meeting dates.

Meeting 13 - 25/01/2024

- Asked about the structure of the year and if there were any specific dates to watch out for and was told that the only date needed is the dissertation due date and to focus on that.
- Recommended to make a plan and try to estimate how long I will spend on each section (implementation, evaluation, writing it up etc).
- There will be a reflection process, how long things took, were they challenging etc.
- First thing to do is to get the hanging cloth working but do it in a way that its easy to modify for other scenarios like the sphere cloth.
- Babis mentioned an idea of parameterising the attachment points in time so that it can be added to a moving object (e.g. cape on a human character moving).
- Dont be shy with figures in the end.
- Base title can be "real time cloth simulation using position based dynamics" but can add extra stuff to make it unique
- Overall breakdown should be
 - 60% implementation
 - 20% writeup
 - 20% evaluation

Meeting 14 - 01/02/2024

- Created a plan with dates I wanted parts finished by (implementation/writeup/eval etc)
- Had a few more questions regarding the Unity setup before I really get started with the implementation

Meeting 15 - 08/02/2024

- Got a basic mesh creator working, fixed particles and constraints that use springs (Mass spring system).
- Asked Babis' opinion if i was doing any bad practices but it seems fine so far

Meeting 16 - 15/02/2024

- Implemented a basic PBD setup.
- Asked about glm vec3 conversion from a c# vector3 and it should work fine.
- Babis showed a video of a character interpolating between poses and the cloth moving to fit which was interesting.
- Need to speed up a bit on progress for next week.

Meeting 17 - 22/02/2024

- The current way of generating mesh and constraints using grid_size isn't great because it only works for a square x by x grid. Need to rework it and create constraints from adjacent triangles instead. Will be a bit tricky but it is probably necessary.
- Next feature after that to create is the click and drag feature.

Meeting 18 - 29/02/2024

- Shared all my stuff on screen and showed the new features like shear constraints, stiffness slider and all the new functions (triangles instead of grid size). Looks good so far
- Babis suggested a cool way of doing a more realistic wind with 3d perlin noise using the x and y of vertex to make the wind point different directions. He noted that since i already have working wind its better to focus on the more urgent things.
- He also suggested an unordered set for constraints as its a little faster but since i add it to a vector anyway it isn't that important.
- I asked about a section of the paper where it states that they had to also use collision checking with rigid bodies in case they fall through the triangles but this isn't applicable to this project as the collision checking will only happen with a big sphere on scenario2, so just the cloth collision is required.
- I asked about his thoughts on priority tasks and it seems the next steps are:
XPBD -> Bend constraints if i can do it in an hour-ish -> fix mouseLocation bug with the drag feature -> get the collision stuff working
- He recommended for me to use debug and breakpoints for the dll, not sure why i wasn't doing that in the first place.

Meeting 19 - 07/03/2024

- Showed my extended position based dynamics demo, looks a bit more stable than PBD. 10 substeps.
- Explained that my bend constraints are completely fine, the harder angle ones would be a bit better but are more complicated to implement.
- Babis recommended checking out the Unity recorder plugin and to implement a mass recording system. So that when i press a button it records a bunch of experiments which will be very useful for the results section.
- Babis also explained a way to reset the cloth object every time its run instead of needing to .clear() every vector. (g_ClothSim = {};) It would be a tiny bit slower but wouldn't need to clear new vectors. Up to me if i want to change it.
- Asked if i could send an unlisted youtube video showing the simulation as the teams share screen isn't great for showing it.

- Sent a video and got good and helpful feedback.

Meeting 20 - 14/03/2024

- Showed my collision code, looked good but Babis noticed that it looks a bit odd when the cloth weaves with itself and recommends trying to get self collision implemented to fix that
- Showed my recorder feature, looks good

Meeting 21 - 21/03/2024

- Discussed my layout for the methodology section. Overall reasonable, Babis suggested that I place the scenarios section in the results which is fair. Also recommended to merge mesh creation into initialization which is a good idea.

Meeting 22 - 28/03/2024

- Shared my progress on writing the diss, good so far.
- Asked about the evaluation/reflection part to get some clarity on what should actually be in there.

Meeting 23 - 04/04/2024

- Asked Babis about the poster session, just general questions about how it will work.
- Asked how liberally I should be placing code snippets in the diss, was told not often, because no one really wants to just look through lines and lines of code, better to explain how it works. Use lots of figures though.

Meeting 24 - 11/04/2024

- Asked when the Viva usually is, just any time within 3 weeks of the submission it seems.
- The captions on figures are generally below the figures which is an easy enough fix
- Babis would send feedback of the diss after the meeting, so I can improve little bits before submission.

D Poster

Real Time Cloth Simulation using Extended Position Based Dynamics

Matthew Lenathen¹

¹Edinburgh Napier University

Summary

This project aimed to implement Extended Position Based Dynamics (XPBD), a specific method of simulating cloth, within the Unity physics framework. It would be implemented alongside a mass-spring system and the original Position Based Dynamics (PBD) to compare each method. The findings revealed that XPBD improved upon PBD by making stiffness independent of time step. It also fixes the issue of solver iterations affecting stiffness by replacing them with substeps. Overall, XPBD is a very useful method in simulating cloth and other deformable bodies.

Introduction

Realistic cloth simulation is integral to a number of applications across many industries such as film, games development and virtual reality. Combining maths, classical mechanics and programming, cloth simulation aims to accurately replicate the behaviour of these objects in real time environments. Among the many approaches available, Extended Position Based Dynamics (XPBD) stands out due to its simplicity and robustness in simulating cloth and other deformable bodies. This poster presents the implementation and results of utilising this method within the Unity physics simulation framework. Unity scripts are written in C#, but a C++ dll plugin was written to handle the simulation code, as C++ is much more efficient with vector calculations.

Methodology

In physics based animation, objects are represented with vertices that make up a mesh that is displayed to the screen. PBD and XPBD treat these vertices as particles with properties such as mass, position and velocity. Using the forces acting on the particles such as gravity and wind, the predicted particle position can be calculated. All constraints are then worked on, and a new velocity is calculated by taking the difference of the current particle position, and the predicted particle position divided by delta time. Delta time is fixed at 0.02 seconds but experiments were performed at different time steps.

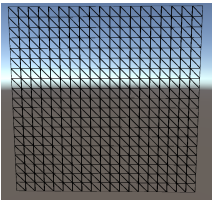


Figure 1: A wireframe of a cloth mesh.

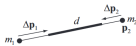


Figure 2: Projection of a constraint between two particles. Figure adapted from [1].

Figure 2 shows the general idea behind constraints. During the current time step of the simulation, the predicted positions are modified by some vector Δp so that they better satisfy the distance constraint d . In XPBD, the simulation loop iterates through multiple substeps. Each substep involves recalculating the predicted positions and adjusting them to satisfy the constraints more accurately. This iterative process ensures the constraints are satisfied to a higher degree and results in a more precise and accurate simulation.

The distance corrections Δp_1 and Δp_2 are calculated as:

$$\Delta p_1 = -\frac{w_1}{w_1 + w_2 + \frac{\alpha}{\Delta t}}(p_1 - p_2) - d\frac{p_1 - p_2}{|p_1 - p_2|}$$
$$\Delta p_2 = \frac{w_2}{w_1 + w_2 + \frac{\alpha}{\Delta t}}(p_1 - p_2) - d\frac{p_1 - p_2}{|p_1 - p_2|}$$

Where w is the inverse mass of the particles, and d is the rest or goal distance, and α is the compliance factor.

The stiffness of the simulation can be adjusted by modifying the compliance factor. The simulation is infinitely stiff when $\alpha = 0$, the effects of stiffness can be seen in Figure 3.

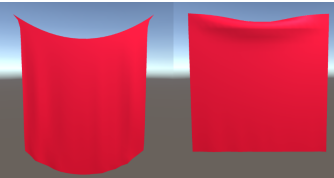


Figure 3: Two cloths with different stiffness values

The user is also able to interact with the cloth by clicking and dragging it. This works by casting a ray from the camera to the cloth, finding the nearest particle to the click and making it static. This functionality enables users to test extreme movements and assess the behaviour of the cloth simulation more effectively.

Another scenario was also implemented with collision code, where a horizontal cloth falls and collides with a sphere. This was to test how well the constraints perform when collisions are also happening in the same time step.

Collision works by checking if the distance from the particle to the centre of the sphere, is lower than the sphere's radius, indicating the particle has collided with the surface. It then calculates a vector to adjust the particle's predicted position out of the sphere. This scenario can be seen in Figure 4.




Figure 4: The horizontal cloth falling on a static sphere

Results

Once all three methods were implemented they were tested through different experiments. The mass-spring system is very unstable at high stiffness and can cause the simulation to explode, whereas PBD and XPBD are unconditionally stable. The mass-spring system was implemented in both C# and C++ to gauge how much faster C++ was, and it was at least a 60fps gain in most scenarios.

The time step stiffness issue with the original PBD is completely solved with the compliance factor in XPBD, saving the developer from manually tuning the stiffness of the system for different time steps. The solver iterations of PBD is also fixed in XPBD by utilising substeps for the whole simulation loop, instead of just looping over the constraints.

A recorder feature was implemented that allows many experiments to be set up in code, and the recorder will queue them up and record videos of each experiment. This was useful in observing how the cloth changes when variables such as substeps, compliance and time step are changed.

Conclusion

In this project, multiple cloth simulation methods were implemented and tested, the mass-spring system, Position Based Dynamics and Extended Position Based Dynamics. The results suggest that the two position based methods offer significant advantages over traditional methods such as increased stability and performance. The implementation of XPBD successfully resolves the long-standing issues present in PBD, such as time step dependant stiffness. The integration of a C++ simulation within the C# Unity environment allowed for the utilisation of helpful features provided in Unity, while retaining the improved performance of using C++.

Future Work

While the base XPBD implementation is good, there are some improvements that could be made with future work. One such improvement would be self collision. This would allow the cloth to interact and collide with itself, leading to increased realism. It is not a trivial problem to solve and one such solution could be the use of spatial hash maps to efficiently check which particles are colliding.

Another scenario could be implemented to further test the method. An example scenario could be clothing on a game character such as a dress. This would test how the cloth would look like in animation or a game. This would most likely require self collision first.

References

[1] Matthias Müller, Bruno Heidelberger, Marcus Hennrich, and John Bucklin. Position based dynamics. *Journal of Visual Communication and Image Representation*, 19(2):109–116, 2007.