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CSC 473 Final Paper - Cloth Simulation

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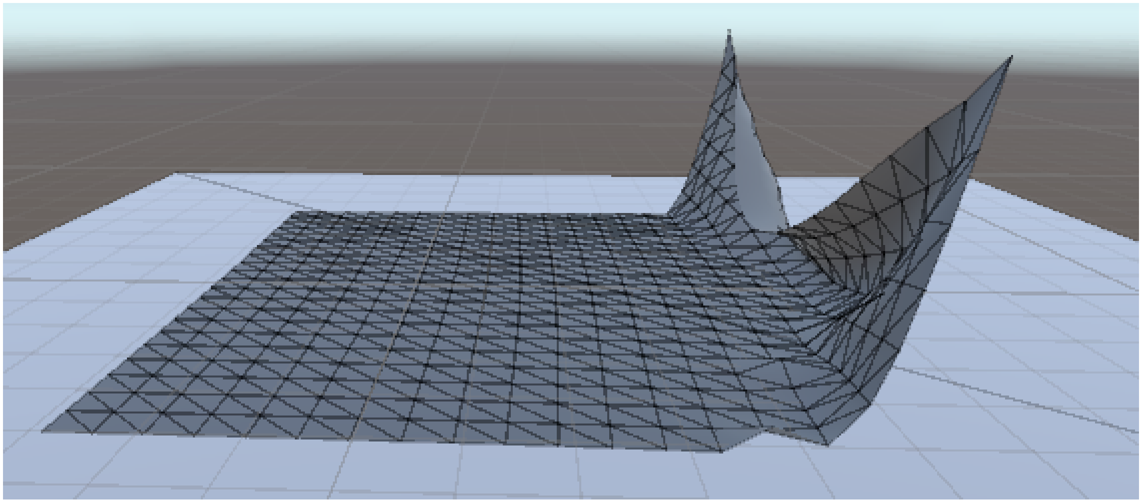

Figure 1: *Replace me with a teaser image of your work!*

Abstract

Cloth simulation is a widely used technique in computer graphics and animation. It involves simulating the physical behavior of a piece of cloth, which can be draped over an object, folded, and moved by forces. Cloth simulation has various applications in video games, films, and virtual reality, where realistic cloth behavior is essential for creating an immersive experience.

In this project, a cloth simulation system was developed using the mass-spring model. The simulation was able to simulate the physical behavior of a piece of cloth under external forces, including gravity and drag. Three types of springs were implemented to simulate the structural properties of the cloth, including stretching, shearing, and bending springs. The collision detection and response algorithm were used to prevent the cloth from penetrating with other objects in the scene.

The evaluation of the cloth simulation system showed some issues related to stability, performance, and accuracy. The solution to these problems included implementing triangle-triangle intersection detection method, optimizing the collision detection algorithm, and adding impulse force in the collision response.

Overall, this project demonstrated the feasibility of implementing a basic cloth simulation system using the mass-spring model. Future work can involve fixing the current issues.

CCS Concepts

• ***Computing methodologies*** → *Collision detection;* • ***Hardware*** → *Sensors and actuators; PCB design and layout;*

1. Introduction

Cloth simulation is a popular area of research in computer graphics. It allows computers virtually replicate fabric materials by accurately mimicking their physical behavior and appearance in a virtual environment, resulting in a more realistic and believable representation. Over the last few years, there are a lot of improvements made in computer hardware and algorithms that allow cloth simulation to generate more complex and realistic physics. As a result, it has become a trending topic in the animation and game development industry, with numerous practical applications such as virtual clothing, flag animations, and more.

The goal of this cloth simulation project is to develop a cloth simulation system that can simulate the physical behavior of the different types of fabric materials in a realistic way possible. Which can contribute to teaching others how cloth is simulated in movies and games.

In this project, I will be using Unity to implement the cloth simulation system. The simulation system is specifically designed to account for both external and internal forces. For external force, there will be gravity and drag. And internal force, there will be structural springs, shearing springs, bending springs, and damping. These are the key elements to creating realistic cloth movements and deformations.

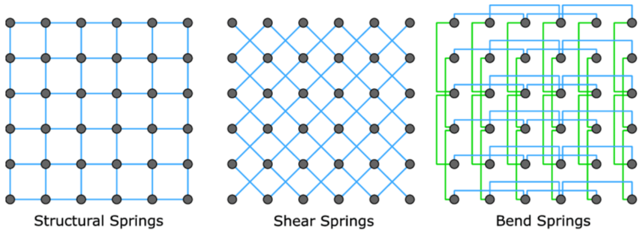

Figure 2: *This is the springs layout inside the cloth*

2. Related Work

Cloth simulation has been an active research area for many years, and numerous methods have been proposed to address the challenges associated with simulating realistic cloth behavior. Baraff and Witkin's work on cloth simulation using mass-spring systems [Baraff and Witkin, 1998] is a fundamental paper that has inspired many subsequent works. The paper proposed a large-step numerical integration method that achieves real-time performance by using a large time step. Volino et al. proposed a simple approach to nonlinear tensile stiffness that improves the accuracy of cloth simulation [Volino et al., 2009]. Their method uses a simple piecewise linear model to approximate the nonlinear relationship between stress and strain.

Bridson et al. presented a method for simulating clothing with folds and wrinkles [Bridson et al., 2003]. The method uses a hybrid simulation technique that combines mass-spring systems with continuum mechanics. The paper focuses on modeling the mechanical properties of clothing, such as stretch, bending, and shearing. Terzopoulos et al. introduced elastically deformable models, which are physically-based models that simulate the deformation of objects using a finite element method [Terzopoulos et al., 1987]. The paper proposed a new method for modeling the elasticity of materials that can handle both linear and nonlinear elasticity.

Finally, Liu et al. proposed a method for fast simulation of mass-spring systems [Liu et al., 2013]. The paper introduces a new algorithm that uses a hierarchical data structure to improve the performance of mass-spring systems. The method uses a coarse-to-fine approach to simulate the behavior of the system, where the simulation is performed at a coarse level first and then refined as necessary.

3. Overview

The cloth simulation is a complex process that involves several components working together to create a realistic and dynamic simulation of cloth behavior. In this overview, we will cover the key elements of cloth simulation, including particles, springs, and collision detection and response.

Particles are the fundamental building blocks of the cloth simulation. A particle-based system consists of multiple particles that form the cloth. The more particles used, the more resolution the cloth will have, resulting in a more realistic simulation.

Springs are used to model the various forces acting on the cloth, such as tension, shear, and bending. Structural springs maintain the overall shape and structure of the cloth, while shear springs resist lateral movements and bending springs maintain the curvature of the cloth. The simulation of these springs is done using numerical integration methods, and damping is introduced to reduce oscillation.

Collision detection and response are crucial components of cloth simulation. Collision detection involves checking whether the cloth has come into contact with other objects in the scene, and there are several methods to detect collisions. Once a collision has been detected, collision response is required to ensure that the cloth reacts correctly. Contact force is used as the collision response in this simulation.

In summary, the cloth simulation requires a particle-based system with interconnected springs to model the forces acting on the cloth. Collision detection and response are also crucial for a realistic simulation. The result is a dynamic and visually appealing simulation of cloth behavior.

3.1. Particles

To implement a cloth, we first have to talk about how a cloth is rendered. In this project, I will be implementing a particle-based system that consists of multiple particles that form the cloth. The number of particles collated to the resolution of the cloth, which meant the more particles the more realistic the cloth looked.

3.2. Springs

The particles are interconnected by springs. Springs are used to model the various forces acting on the cloth, such as tension, and bending. There are three types of springs commonly used in cloth simulation: structural springs, shear springs, and bending springs Figure 2.

Structural springs are the most basic type of springs used in cloth simulation. They are located between each particle's adjacent neighbor. They represent the tension forces between adjacent particles in the cloth mesh. These springs are used to maintain the overall shape and structure of the cloth. Shear springs are used to model the resistance of the cloth to shearing forces. These forces occur when the cloth is subjected to lateral movements, such as wind or other external forces. They are used to connect pairs of neighboring vertices that are offset in the direction of one of the perpendicular axes. Bending springs are used to model the bending resistance of the cloth. These springs are used to maintain the curvature of the cloth and prevent it from collapsing under its own weight. The bending spring made the cloth bend and fold in a more realistic way, which can greatly enhance the visual. They exist on every other particle.

All three types of springs work together to simulate the various forces acting on the cloth. The structural springs provide the overall shape and structure of the cloth, while the shear and bending springs provide the resistance to shear and bending forces. The simulation of these springs is done using numerical integration methods forward Euler method to solve the equations of motion of the particles in the cloth mesh.

The method of calculating the force on each type of spring is the same.

$$\vec{F}ij = -ks(l_0 - \|\vec{r}ij\|)\frac{\vec{r}ij}{\|\vec{r}_{ij}\|}, \tag{1}$$

where $\vec{F}ij$ is the force acting on particle i due to particle j, k_s is the spring constant, l_0 is the rest length of the spring, $\vec{r}ij$ is the vector from particle i to particle j, and $\|\vec{r}_{ij}\|$ is its magnitude.

To calculate the spring force we will need to know each particle's current position, the spring rest length, the spring current length, and the coefficient stiffness of the spring. Because the system used springs. This will create oscillation in the cloth, which can make the cloth look unnatural. To solve this problem, I have introduced damper force into each spring. This will reduce the oscillation that is introduced in the springs.

The calculation of the damper force requires the coefficient of the damper and the velocity of the particles.

$$F_{damp} = -k_d(\vec{v}_i - \vec{v}j)\cdot\vec{d}ij \tag{2}$$

where F_{damp} is the damping force, k_d is the damping coefficient, $\vec{v}_i$ and $\vec{v}j$ are the velocities of particles i and j, respectively, and $\vec{d}ij$ is the vector between particles i and j.

3.3. Collision

Collision detection and response are crucial components of cloth simulation. Without these, the simulated cloth would simply pass through other objects in the scene, resulting in an unrealistic simulation. In this section, we will discuss collision detection and response in detail.

Collision detection involves checking whether the cloth has come into contact with other objects on the scene. There are serval ways to detect collision in cloth simulation such as sphere testing, ray-casting, and mesh collision detection. In this simulation, It uses ray-casting detection. This uses the particle's information to foresee the next position and cast a ray from the current position to the next position of the particle to check for an intersection Algorithm 1.

Once a collision has been detected, collision response is required to ensure that the cloth reacts correctly. There are several ways to respond to collision, including impulsing force toward the cloth particle and contact force where changing the direction of the particle. For the simulation, it used contact force as the collision response Algorithm 2.

Algorithm 1 Ray-casting collision detection

$L = p_{next}$ - p_{cur}
if L hit a mesh **then**
  Calculate collision response on p
end if

Algorithm 2 Collision response

$v_N = (p_{velocity}\cdot hit_{normal}) * hit_{normal}$
$vT = p_{velocity} - vN$
$v = -0.001 * vN + vT$
$force_p = (p_{mass} * (v - p_{velocity})/\delta t$

4. Evaluation

Our cloth simulation project was evaluated based on the accuracy of the cloth generation and the performance of the simulation. The accuracy of the cloth generation was found to be good, with the cloth taking on a realistic appearance and behaving in a physically accurate manner Figure 3. However, the collision detection and response was a failure, with the cloth penetrating through the collision objects instead of interacting with them as expected Figure 4. This could be due to the limitations of our collision detection algorithm and requires further improvement in future work.

Regarding the performance of the simulation, we observed that the system performed well on low-resolution cloth meshes. However, when increasing the resolution of the cloth mesh, the simulation started to drop frames, resulting in a noticeable decrease in the real-time performance of the system. This limitation is likely due to the computational complexity of simulating high-resolution cloth meshes and could be improved with more efficient algorithms or hardware acceleration.

Overall, the results of our cloth simulation project demonstrate that the accuracy of the cloth generation is good, but there is room for improvement in the collision detection and response. The performance of the simulation is good on low-resolution cloth meshes but needs further optimization for higher resolutions.

5. Conclusion

In conclusion, while the cloth generation using the mass-spring system has yielded good results, the performance of the collision detection and response mechanism did not meet the initial expectations. Further improvements in collision handling would be required to achieve a fully realistic and immersive cloth simulation. Nonetheless, this project provides a foundation for future work in the field of cloth simulation, demonstrating the importance of accurate and efficient collision handling for achieving a more realistic simulation. The insights gained from this project could potentially inform the development of more advanced techniques for cloth simulation, facilitating the creation of more lifelike and compelling virtual environments in various applications such as video games, animation, and virtual reality experiences.

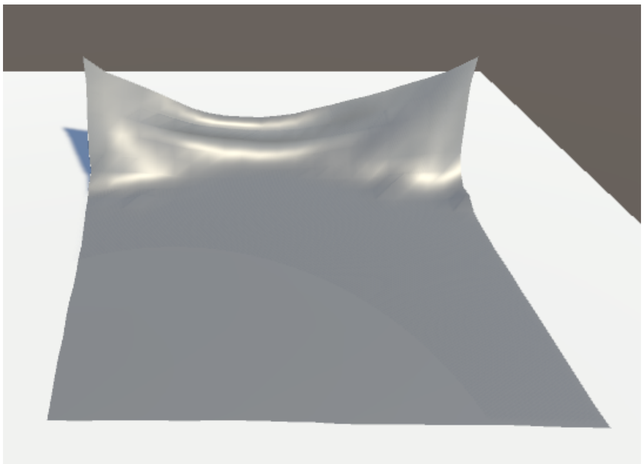

Figure 3: *Collision detection on flat surface*

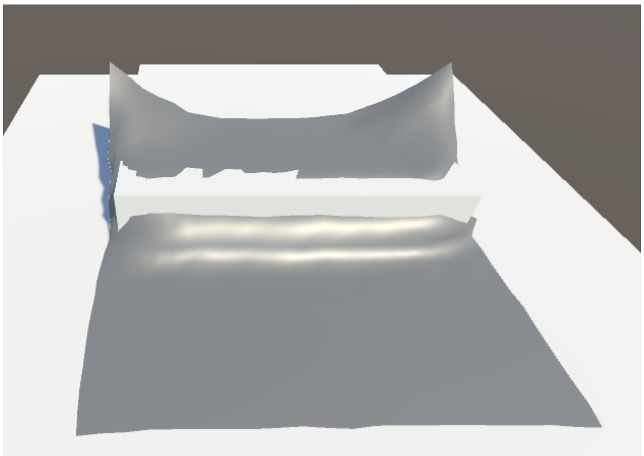

Figure 4: *Collision detection failed*

5.1. Challenges

There are multiple reasons to make cloth simulation challenging. One of the significant challenges is the complexity of the physics involved in simulating the motion of cloth realistically. Cloth motion is affected by several physical forces, including tension, bending, and shearing forces. These forces must be accurately modeled to create a realistic-looking cloth.

Another challenge is the computational cost of simulating cloth. Cloth simulation requires a high computational cost as it involves the interaction of numerous particles and the calculation of the forces between them. The number of particles in a cloth simulation can be in the order of thousands or even millions, which can make simulation time-consuming.

Another issue is the accuracy of the collision detection and response. Cloth simulation needs to handle complex collision interactions with other objects in the scene accurately. Inaccurate or inefficient collision detection and response can lead to cloth penetration and unrealistic results.

Furthermore, the design of the cloth itself can pose challenges. The design must be optimized to work well with the simulation method chosen. The cloth mesh should be free of holes or other anomalies, as they can lead to incorrect simulation results.

Finally, there is the issue of stability. Cloth simulation can be prone to instability, resulting in oscillations or unrealistic behavior. Various methods, such as adding damping forces or reducing the time step, can be used to improve stability.

5.2. Limitation

There are several limitations to my cloth simulation project. Firstly, the simulation is limited by the number of particles used to represent the cloth. While a higher number of particles leads to a more realistic simulation, it also requires more processing power and can slow down the simulation. As a result, the cloth in my simulation may not be as detailed as desired due to computational constraints.

Secondly, the collision detection and response mechanism in the simulation is not robust enough to handle complex shapes or movements. In situations where the cloth collides with more complex objects or collides with a moving object, the simulation may not respond as expected, resulting in unrealistic behavior.

Thirdly, the simulation does not take into account the effect of environmental factors such as wind or gravity. While these factors can have a significant impact on the behavior of cloth, they are not modeled in this simulation.

Lastly, the simulation is limited by the numerical integration method used to solve the equations of motion. The forward Euler method used in this project is a relatively simple method that can lead to instability and inaccuracies in the simulation. More advanced numerical methods, such as the Verlet method or Runge-Kutta method, can provide more accurate results but can also be more computationally expensive.

Overall, while the cloth simulation project is a good start, there is room for improvement in terms of detail, robustness, and accuracy.

5.3. Future work

As we have seen in the evaluation section, the current state of the simulation system is far from perfect and there are numerous issues that need to be addressed. However, it is not all doom and gloom. In this section, we will explore potential solutions to these problems and propose ways to improve the overall performance and accuracy of the simulation. Through careful analysis and experimentation, we can identify the root causes of these issues and develop strategies to overcome them. By implementing these solutions, we can enhance the realism and fidelity of the cloth simulation, making it a more reliable and effective tool for a wide range of applications. So let's dive into the challenges we faced and explore the innovative solutions we have developed to push the boundaries of cloth simulation technology.

The accuracy of the simulation is inaccurate. This is a problem cause by ray-casting collision detection. Due to the ray-casting method only check each particle and its next position, the edges in between particle got ignored. This resulting interpenetrate on pointy objects. The solution for this problem would be changing the collision detection into using mesh detection, where it will check the entire triangle mesh instead of a point on the cloth. The triangle-triangle intersection method however will be costly, which can lead to our second problem performance issue. This will be discussed later in the paper.

The cloth simulation also didn't take care on the real-time interaction with moving mesh. This resulting cloth passing through moving objects, which is unrealistic. The root of this problem is that the simulation didn't include the impulse force when the collision happened.

The performance of the simulation can become unstable when the number of particles increases or using the new triangle-triangle intersection detection method. This meant the simulation system requires some optimization. One of the solutions to this problem is to create an AABB tree to store all the triangle mesh, this can reduce the number of redundant detection on some of the mesh.

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