CLOTH SIMULATION USING AN ENHANCED CATMULL-CLARK SUBDIVISION SCHEME AND COLLISION DETECTION IN A VIRTUAL ENVIRONMENT

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ABSTRACT. *Subdivision surface techniques smoothen the surface of any 3D object by splitting the polygons into smaller sub-polygons. However, most methods of subdivision encounter the same problem when dealing with extraordinary points. This project aims is to implement an enhanced Catmull-Clark subdivision scheme and simulated cloth that can detect and identify the collision of an object against the simulated cloth in a virtual environment. The original Catmull-Clark subdivision scheme was enhanced by manipulating the weights present in the original scheme while adhering to a few rules. The cloth used a mass-spring model to be initialised, and the enhanced subdivision scheme was integrated into this model. Then, the collision detection was performed based on the bounding volume approach, and an appropriate collision response was used to simulate the behaviour of the cloth in real life. Experiments and tests were conducted to evaluate the smoothness of the enhanced subdivision scheme and the computation time. The enhanced subdivision scheme was only able to create an acceptably smooth surface until the second iteration of the subdivision. On the third iteration, noticeable sharp points were present, which indicated that the enhanced subdivision scheme did not improve the original scheme. Additionally, the execution time for the enhanced subdivision scheme was insignificantly longer compared to the original scheme for all the levels of subdivision. The frame rate test showed that the cloth simulation ran at the average rate of 43.572 fps, which was within the acceptable range. In conclusion, this research focuses on creating a cloth simulation that implemented an enhanced Catmull-Clark subdivision scheme and collision detection. However, the proposed enhancement for this scheme can be improved to account for the subdivision at individual cases of extraordinary points.*

KEYWORDS. *Catmull-Clark subdivision surface; collision detection; cloth simulation; extraordinary points; weights*

INTRODUCTION

The advancement of computer is staggering due to the introduction of many image processing and visualisation techniques in the world of computer graphics. One of such techniques that was used in this project was the *subdivision surfaces*. Subdivision surfaces refer to the method used to represent smooth surfaces from its course polygon mesh. Though there are many different techniques to perform subdivision surfaces, the basic principle or idea is to recursively divide the surface of a polygon mesh to create smaller faces that would be better for rendering a smoother surface (Salomon, 2011). Another aspect of computer graphics that is discussed in this project is the *collision detection*. Collision detection refers to the intersection of two objects when an object is acted upon another object. Detecting the collision between objects is the key to creating the appropriate response to the collision (Kockara *et al*.,2007). Subdivision surfaces and collision detection are just some of the techniques used and tested in a virtual environment. Nowadays, where augmented reality and virtual reality technology dominate the world stage, there are still some game developers and testers who use virtual environment to simulate the real world for the user. *Cloth simulation* is an excellent choice to showcase the application of subdivision surface techniques and collision detection in a virtual environment. Most researchers use cloth simulation to test the subdivision surface technique that they develop because the cloth used in making clothes have smooth surfaces (Jiang, Wang & Lui, 2008).

Collision detection is commonly associated with the computational difficulties of identifying the intersection between two objects (Lai & Kang, 2009). Meanwhile, to simulate a smooth surface that imitates cloth using subdivision schemes requires a carefully constructed program to avoid jagged edges in the simulated cloth. However, the challenge is to utilize an efficient collision detection technique that will be able to detect only the intersection of the object with the simulated cloth. The gap that exist in in problem is the ability of subdivision techniques in replicating the movement of cloth when an object collides with it as it would do in real life. If the subdivision is done right, it would ensure that the cloth moves fluidly and is able to react appropriately towards object collision (Choi & Ko, 2005).

There are several topics to be familiar with in order to conduct cloth simulation and collision detection, which include understanding virtual environment, techniques of subdivision surfaces and collision detection as well as comprehending the nature of cloth simulation. *Virtual environment* has been used extensively in various fields especially in creating a variety of simulations. The use of virtual environment helps users experience a certain scene with more clarity and understanding by being able to observe the changes that can be made virtually. The virtual environment can be used to develop many interesting programs to teach people about techniques while allowing them to interact with the program (Zhen *et al.*, 2010).

S*ubdivision surface techniques* is a method used to create smooth surfaces. It is categorised under two schemes namely the approximating scheme and the interpolating scheme. The approximating scheme does not use the endpoints of the control mesh in the final subdivided mesh. Several schemes can be used under this method including the Catmull-Clark subdivision scheme, the Doo-Sabin subdivision scheme, the Loop subdivision scheme, the Mid-edge subdivision scheme, and the $\sqrt{3}$ subdivision scheme. Each scheme has its advantages and disadvantages, in addition to having different requirements to begin the subdivision process. Meanwhile, the interpolating scheme includes the endpoints in the final subdivided mesh because the endpoints are interpolated. The most popular scheme under this subdivision surface technique is the butterfly scheme (Dyn *et al.*, 1900). Due to some limitations in the butterfly scheme, a modified scheme has been proposed. Researchers have developed many versions of the modified butterfly scheme to overcome its limitations, to improve the product of the subdivision surface mesh, or to improve computation. The smoothness of a surface can be evaluated by determining the continuity and the number of times a parametric equation can be differentiated (Warner, 2013). Additionally, the geometric continuity can be assumed based on the parametric continuity.

In *collision detection*, the process of determining whether the objects are intersecting can be done in two stages: the broad-phase and the narrow-phase (Ericson, 2005). The broad-phase of collision detection works to decide which objects will proceed with the narrow-phase. Three methods can be used in this phase namely an exhaustive search, a coordinate sorting, and multi-level grids. The narrow-phase of collision detection uses various approaches to determine if the collision between objects occurs. Four categories of approaches can be used in this phase: feature-based, simplex-based, volume-based, and spatial data structures. From the research findings, researchers prefer using bounding volume and bounding volume hierarchies in the broad-phase and narrow-phase collision detection respectively (Hubbard, 1993).

Moving into the application of subdivision surfaces and collision detection, one can observe that these two techniques are extensively used in various fields such as animations, games, and simulations (Liu *et al.*, 2012). The usage of these techniques in the fields mentioned above increases the appeal it holds for the user because the effects are realistic and follow the laws of the real world (de Oliveira *et al.*, 2014). Focusing solely on cloth simulation, one can see the importance of both techniques. They offer the simulation realism by being able to emulate the surface, movements, and dynamic complexity of the cloth from real world (Wu & Peters, 2014). Due to the constant usage of subdivision surface techniques and collision detection in the industry, these methods have evolved exponentially since its first appearance (Ng & Grimsdale, 1996).

METHODOLOGY

This project underwent two phases, in order to successfully develop the prototype. The first phase, or the research phase, consisted of gathering information related to the research topic followed by the second phase, where the techniques that were studied in the research phase were selected and implemented in the development of the prototype system. Then, the completed prototype was evaluated. The architecture system was divided into three parts namely input, process, and output, as shown in Figure 1 below.

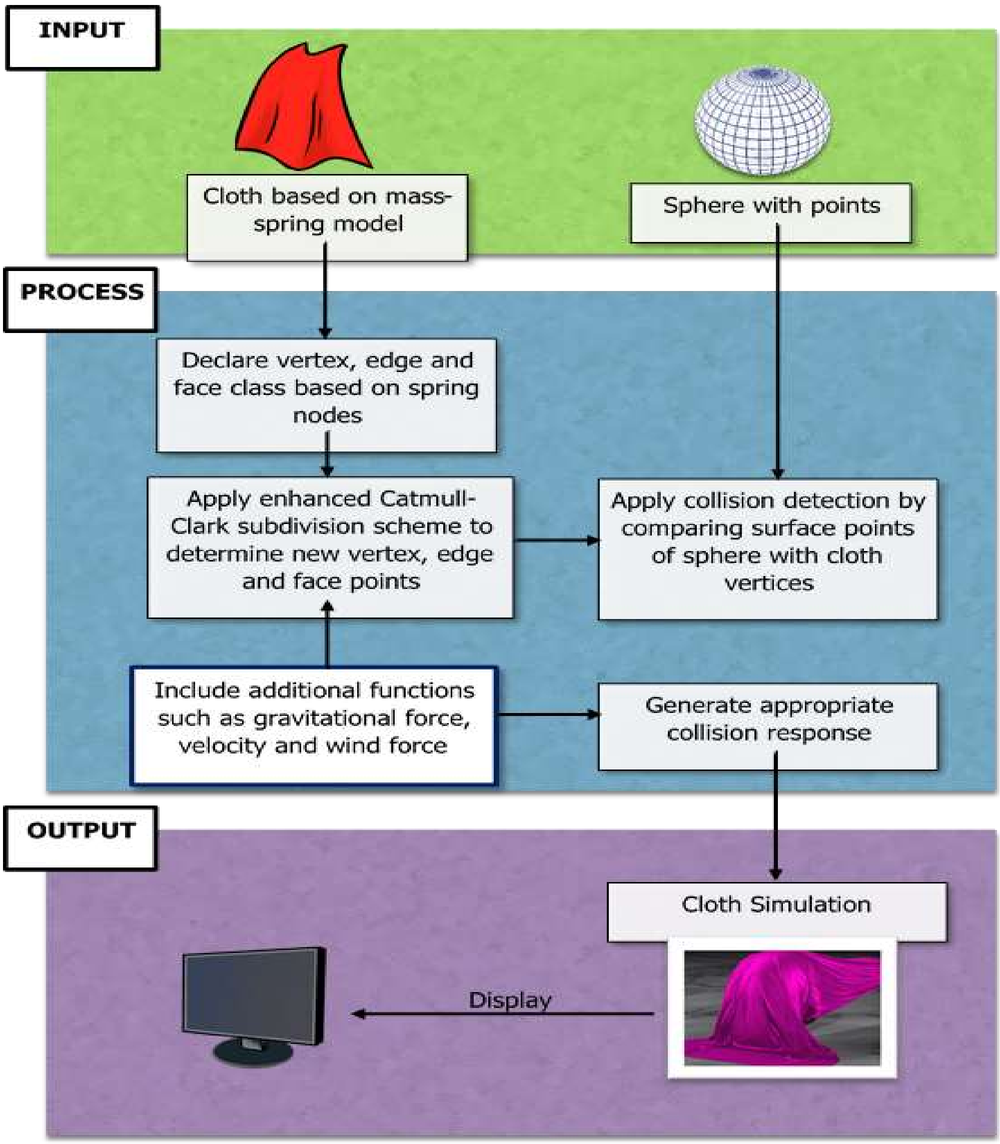


Figure 1: Overview of Architecture

The process was further divided into the Catmull-Clark subdivision surface technique with the enhancements and collision detection on the simulated cloth, which will be discussed in the next section. Finally, the output seen by the user was the result of the execution of the process stage. The details of the implementation of the process stage are briefly described below.

1. ***Catmull-Clark Subdivision Scheme***

   The algorithm in Figure 2 was used to calculate the new vertex for this subdivision scheme (Catmull & Clark, 1978).

```
Algorithm for Catmull-Clark Subdivision Scheme
for all Faces in the mesh do
    Create a new face point
    Face point value = AVERAGE of SUM previous points in a specified face
end for
for all Edges in the mesh do
    Create a new edge point
    Edge point value = AVERAGE of midpoint of previous edge points +
    average of two face points that share the edge
end for
for all Vertices in the mesh do
    Create a new vertex point
    Vertex point value = Equation 2.1
end for
for all the Vertices do
    Connect the points and make the refined mesh
end for
```

Figure 2: Catmull-Clark Subdivision Algorithm

2. ***Enhanced Catmull-Clark Subdivision Scheme***

   Based on the implementation of the original subdivision scheme (the equation used to calculate the new vertex), the original subdivision scheme can be rewritten as in (1), because the incident edge of the selected vertex point is weighted as $\frac{1}{4n^2}$.

$$v' = \frac{Q}{4n^2} + \frac{3R}{2n^2} + \frac{S(4n-7)}{4n^2} \tag{1}$$

   where the weights are as follows: average surrounding face points, $\alpha = \frac{1}{4n}$, average surrounding edge point, $\beta = \frac{3}{2n}$, and vertex point, $\gamma = 1 - \frac{7}{4n}$. Based on the following weights, it was observed that the edge points were given more weight. The ratio of $\alpha{:}\,\beta$ was 1:6, whereas $\alpha + \beta + \gamma = 1$. Through this understanding, the enhanced technique was considered as a more evenly distributed ratio to compute the new vertex point at extraordinary points. The implementation of the extraordinary points for the enhanced Catmull-Clark subdivision scheme is shown in (2).

$$v' = \frac{Q}{n} + \frac{6R}{n} + \frac{S(n-7)}{n} \tag{2}$$

3. Collision Detection

Collision detection was the second process to be implemented into the system prototype. In this project, a simple collision detection using a sphere bounding volume and collision response were used. The distance between the points on the sphere and the cloth were evaluated using (3), which was then used to compare it with the radius of the sphere.

$$distance = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2 + (Z_2 - Z_1)^2} \quad (3)$$

where (X_1, Y_1, Z_1) are the coordinates of a point on the sphere and (X_2, Y_2, Z_2) are the coordinates of a vertex from the cloth. If the distance is smaller than the radius, then a collision has occurred at that particular point on the cloth with the sphere. Based on this assumption, the collision response was calculated.

IMPLEMENTATION

1. Cloth simulation

The cloth simulation used in this project was created using a mass-spring model (Baraff & Witkin, 1998). The information of the cloth (the vertex) was stored in an array and declared as a struct typedef. Then, the cloth used a bitmap to create an interesting texture for the cloth.

Since the mass-spring system only uses vertices, two other classes were created to declare the edge points and face points. The implementation of the subdivision, collision detection and other functions were integrated into each vertex of the cloth in the mass-spring model. Therefore, each case of the cloth (i.e. the corners, edges, and the remaining) had a conditional statement, which enabled the triggered functions simultaneously.

2. Enhanced Catmull-Clark Subdivision Scheme

The enhanced subdivision scheme was integrated into the cloth simulation using the function calc_subD(), as shown in Figure 3. The new vertex was calculated using the formula in the previous section. Additionally, the condition used to implement this function in the cloth simulation was, when the valence, $n \leq 4$, then the original method was used to compute the new vertex, otherwise, the enhanced method was used.

```
Function: calc_subD()
int p1, p2
vertex centroid, center, newEdge, newVertex
FOR p1 equal to 0, p1 less than n, increase p1 count
    FOR p2 equal to 0, p2 less than n, increase p2 count
        Centroid = Calculate face point
        Center = Calculate midpoint of edges
        newEdge = average of midpoint of adjacent edges
        newVertex = calculated using enhanced subdivision
        scheme
    ENDFOR
ENDFOR
UPDATE the vertex normals to hold the newVertex points
DEFINE spring_node[][] position as updated newVertex
```

Figure 3: Algorithm to integrate subdivision into cloth simulation

3. Collision Detection

Similarly, the collision detection was used in the cloth simulation by implementing the pseudocode in Figure 4. The equation from the previous section on calculating distance was used to evaluate if the two objects collided.

```
Aim: Collision detection and collision response
COMPUTE dist2ball: distance between cloth and sphere using
Eq. 3.4
IF dist2ball is smaller or equal to radius of sphere +0.05
     INITIALIZE temporary vertex for cloth
     COMPUTE spring vector distance using Equation 3.4
     IF spring vector distance is equal to 0
          INITIALIZE spring vector distance as 0.0000001
     ENDIF
     NORMALIZE spring node
     COMPUTE ball vector by finding the difference between
               spring node position and ball position
     COMPUTE ball vector distance using Equation 3.4
     IF ball vector distance is equal to 0
          INITIALIZE ball vector distance as 0.0000001
     ENDIF
     NORMALIZE ball vector
     COMPUTE dot product of spring node and vector ball
     COMPUTE vn: product of ball vector and dot product
     COMPUTE vt: difference between spring node and product
               for ball vector and dot product
     COMPUTE difference of vt-vn
     COMPUTE product of temporary vertex position, spring
               vector distance and damping
     UPDATE vertex position after collision
ENDIF
```

Figure 4: Pseudocode used to implement collision handling in cloth simulation

4. Output

Figure 5 shows the output of the cloth simulation at different conditions.

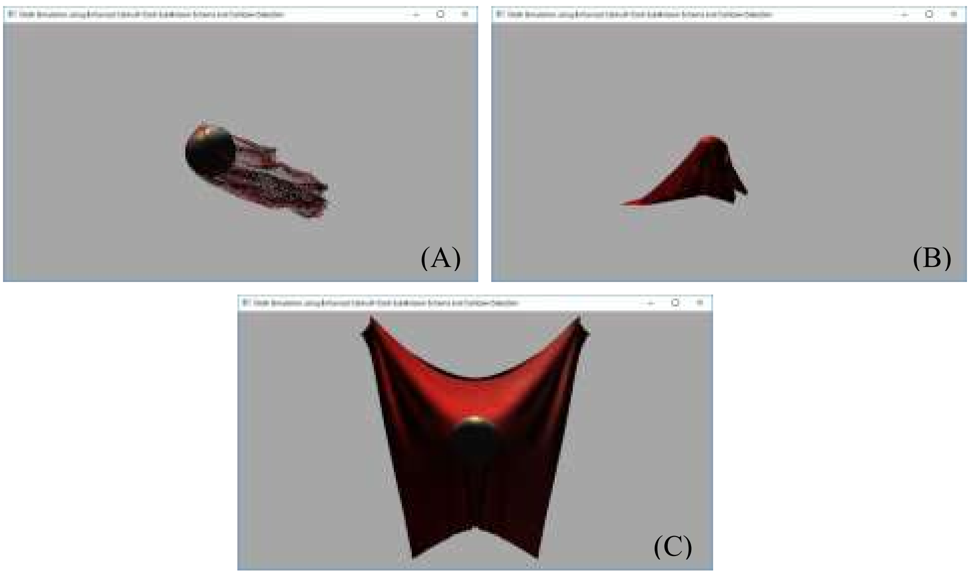


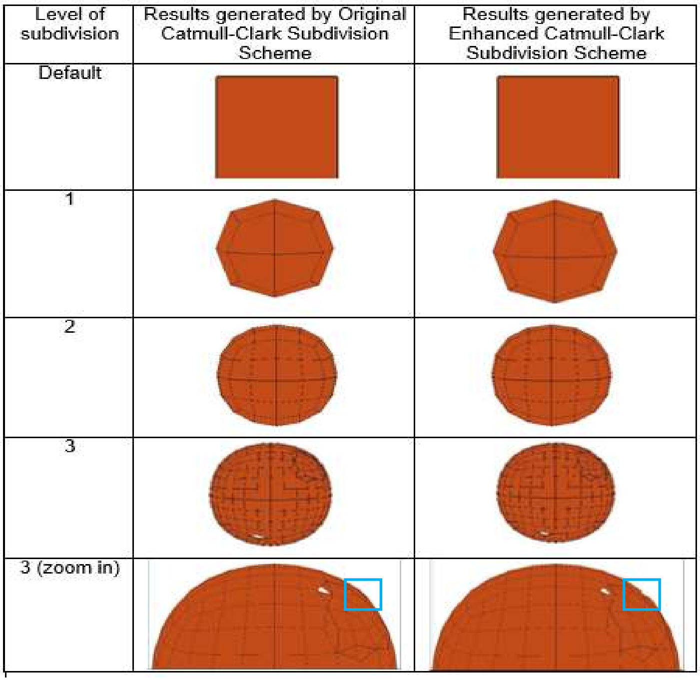
Figure 5: (A) Wireframe of cloth colliding with sphere and wind force enabled during simulation (B) Cloth colliding with sphere and anchor points released during simulation (C) Cloth simulation with texture enabled

EXPERIMENTAL RESULTS

1. *Smoothness test*

A smoothness test was conducted using the parametric equation, where it was found that the original and enhanced Catmull-Clark subdivision scheme had C^1 continuity at extraordinary points. Therefore, smoothness was evaluated through visual observation. The results are shown in Table 1 below.

TABLE 1: Results of the Original and Enhanced Subdivision Schemes



By comparing the subdivision at level 3 in Table 1., it showed that the enhanced method had a small dent, as shown in the blue square. Therefore, the enhanced method did not perform as well as the original method.

2. *Computation time at each level of subdivision*

The tables below show the computation time for both methods for each level of subdivision. By comparing the results, it showed that there was only a small difference between the computation times for both subdivision schemes. The enhanced subdivision scheme took slightly longer due to the conditional statement used in its implementation.

TABLE 2. Execution Time test results for Catmull-Clark subdivision scheme

Experiment	Level 1	Level 2	Level 3
1	0.00233	0.00921	0.03899
2	0.00232	0.00905	0.03921
3	0.00233	0.00910	0.03806
Average	0.00233	0.00913	0.03875

TABLE 3. Execution Time test results for enhanced Catmull-Clark subdivision scheme

Experiment	Level 1	Level 2	Level 3
1	0.00243	0.00879	0.03701
2	0.00296	0.00969	0.03809
3	0.00336	0.01132	0.04248
Average	0.00292	0.00993	0.03919

3. ***FPS test***
   FPS is a utility tool used to evaluate the frame rate of the cloth simulation. Based on the 24 log records, the average fps was 43.752 fps, which was recorded on a device running on 16Gb RAM, 2.5 GHz dual-core Intel Core i5 processor and an Intel HD Graphics 4000, 1536 MB processor graphics card. This result is considered to be acceptable since the minimum frame rate for any animation to produce smooth output is 30 fps. Through the observation of the cloth simulation, the prototype did not suffer any major lag issues due to the collision handling process. The subdivision scheme was directly applied to the cloth model and it was only implemented at the first level to help reduce computation issues and to avoid lags in the program.

CONCLUSION

This project aimed to implement the enhanced Catmull-Clark subdivision scheme to a cloth simulation and to apply the collision detection to the cloth. The original Catmull-Clark subdivision scheme was enhanced by modifying different weights for the extraordinary points, where the valence was not equal to 4. Based on the experiments to evaluate the enhanced subdivision surface technique with the original technique, the enhanced subdivision scheme did not perform as well as expected, but the results were still acceptable. The enhanced subdivision scheme was then applied to a mass-spring model of a cloth, and the collision handling was applied to the cloth simulation.

The cloth was build using a mass-spring model, which used an array to store the information of vertices. Then, the edge and face information were initialized using the stored information of the vertices from the array. Next, the enhanced subdivision scheme was integrated into the mass-spring model of the cloth.

The collision detection was applied to the cloth using a simple algorithm to check if the points on the cloth intersected the points initialized on the sphere by comparing the distance of the points of the cloth and the points on the sphere with the radius of the sphere. Then, an appropriate response was given by the cloth to mimic how the cloth would have reacted in real life.

Additionally, the simulation had an added function of enabling wind forces. This created an interesting simulation in the virtual environment. The cloth simulation was successfully rendered at an acceptable frame rate and the collision handling was executed well.

REFERENCES

Baraff, D., & Witkin, A. 1998. Large Steps in Cloth Simulation. *Proceedings of the 25th annual conference on Computer graphics and interactive techniques*, July 1998, ACM, pp. 43-54.

Catmull, E., & Clark, J. 1978. Recursively Generated B-spline Surfaces on Arbitrary Topological Meshes. *Computer-Aided Design*, **10** (6): 350-355.

Choi, K. J., & Ko, H. S. (2005). Research problems in clothing simulation. *Computer-aided design, 37*(6), 585-592.

de Oliveira, S. M., Vidal, C. A., Neto, J. B. C., de Carvalho, L. L., & Maia, J. G. 2014. Cloth Simulation with Triangular Mesh Adaptivity. *27th SIBGRAPI Conference on Graphics, Patterns and Images,* August 2014, IEEE, pp. 235-242.

Dyn, N., Levine, D., & Gregory, J. A. 1990. A Butterfly Subdivision Scheme for Surface Interpolation with Tension Control. *ACM transactions on Graphics (TOG)*, **9** (2): 160-169.

Ericson, C. 2005. Real-time collision detection. CRC Press.

Hubbard, P. M. 1993. Interactive Collision Detection. *Virtual Reality, 1993. Proceedings IEEE 1993 Symposium on Research Frontiers,* October 1993, IEEE, pp. 24-31.

Jiang, Y., Wang, R., & Liu, Z. (2008, November). A survey of cloth simulation and applications. In *2008 9th International Conference on Computer-Aided Industrial Design and Conceptual Design* (pp. 765-769). IEEE.

Kockara, S., Halic, T., Iqbal, K., Bayrak, C., & Rowe, R. 2007. Collision detection: A survey. In *2007 IEEE International Conference on Systems, Man and Cybernetics* (pp. 4046-4051). IEEE.

Lai, K. C., & Kang, S. C. (2009). Collision detection strategies for virtual construction simulation. *Automation in construction, 18*(6), 724-736.

Liu, L., Wang, R., Su, Z., & Wang, F. 2012, November. A Cloth Simulation Method based on Differential Geometric Energy. *Digital Home (ICDH), 2012 Fourth International Conference,* November 2012, IEEE, pp. 1-6.

Ng, H. N., & Grimsdale, R. L. 1996. Computer Graphics Techniques for Modeling Cloth. *IEEE Computer Graphics and Applications*, **16** (5): 28-41.

Salomon, D. 2011. Subdivision Methods. In *The Computer Graphics Manual* (pp. 803-831). Springer, London.

Warner, F. W. 2013. Foundations of Differentiable Manifolds and Lie Groups *(Vol. 94). Springer Science & Business Media*. 5-7.

Wu, X., & Peters, J. 2004. Interference Detection for Subdivision Surfaces. *Computer Graphics Forum,* **23** (3): 577-584.

Zhen, W., Meng, Y., & Shilong, X. 2010. Research and implementation of modelling in virtual environment based on Open GL. *Computer Science and Information Technology (CCSIT 2010)*, 9 July 2010, Bangalore, India: 661-664