Forced-Driven Wet Cloth Simulation based on External Physical Dynamism

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***Abstract*—Cloth simulation remains challenging for past two decades. There are several factors that contribute to this challenge such as, internal and external forces, water, oil and other fluid elements. This paper focuses on simulating wet cloth by considering external forces and water element. Initially, the mass spring technique is used to produce cloth sheet that is composed from collection of matrix point that connects to the spring, then external and internal forces are applied into cloth surfaces. The inner strength is represented by stiffness between springs of cloth particles, while outside forces depend on wind pressure and mass of object that rely on gravity. The wet cloth simulation is started by adding the fluid component into the textile elements which will affect the mass of the cloth itself. The cloth will absorb significance quantity of fluid that will distress the tension between spring particles inside cloth. The experiment has been conducted by simulating the cloth while absorbing the fluid which is controlled by particular equation. It has shown that saturation level of cloth is changing as well as the texture turn to be darker compared to dry cloth. The darkest color of cloth reflects the highest saturation level of the cloth. It also means that cloth cannot absorb more fluid since it is already full in term of capacity. The evaluation is conducted by comparing the dry and wet cloth in terms of motion and physical appearance. It is concluded that the proposed method is able to simulate the convincing wet cloth simulation with high Frame per Second (FPS) rate and realistic motion and appearance. The future work can focus on simulating interaction between fluid and cloth elements to see spoil scene, or washing cloth that remain challenging.**

Keywords—Wet cloth simulation, fabric; mass spring; fluid; wind; gravity forces

I. Introduction

Cloth is attached into daily human life. In order to simulate the cloth, the textile types and its element should be considered and taken into account when do simulation. The cotton or spandex will have different texture and behaviour when come to the simulation. Currently, most of the researchers are focusing on studying the fluid effects toward fabric in real time simulation. Salazar et.al have mention that reducing the cloth rendering complexity by optimising collision detection with AABB collision detection technique [1]. While [2] already touch wet cloth simulation by rendering fluid with absorbent textiles. He used Smoothed Particle Hydrodynamic was used as a method for fluid mechanism, then combined with Fick's Law for computing translation diffusion [2]. The simulation successfully made the fluid spreading toward cloth fabric in real time with convincing appearance. Other researchers tried to focus on geometric technique for producing surface pieces that cover the cloth bending. They also provide sewing typical in deformation weave design and stitching effect like in real world [3]. Mongus et al. have suggested a method to simulate various fabrics (cotton, spandex, wool or silk) by considering its structure, weight and other factors [4]. Cloth and fluid are perfect combination when it comes to realistic simulation, however due to its complexities a lot of aspects remain challenging [4]. Chen et al. have made significance progress by simulating cloth with wet effects. They are fitted the wet cloth into virtual human to see the behaviour of bending and crumpling [6]. As a result, they mention that friction between cloth surface and self-collision detection is major contribution for their works. In addition, underwater cloth simulation [6], soaking technique for fabric [2] and absorbent behaviour of fluid when passing through textile were also studied as well [7]. Despite of previous studies, this research focuses on presenting unique cloth behaviour which is joining the fluid factors, gravity and wind pressure. The simulation of saturated fabric that blowing up by wind and pulled by gravity is the main contribution of this research.

II. Related Works

Cloth modelling has been used as an interactive application in 3D movies, game, advertisement, fashion application. A lot of researchers have been conducted since early 1980, however the deformation model when virtual human moving is very complex and challenging. The main problem is how to render smooth surface while maintaining the fabrics complexity which is composed of warped fibres. The inner strength between cloth fibres is determined by physical factors that can make textile has wrinkle or buckle. Those factors can be simulated can be simulated to produce folding effects and other effects that appear in real world. However, the complexity of the technique during rendering as well as mathematical assimilation is not an easy task to produce a fabric. For almost two decades cloth simulation still struggle with physic force simulation, collision handling between cloth elements (self-collision) and other external object [4], [5]. Fast cloth simulation should consider all external forces to provide dynamic simulation in efficient ways without affecting the performance of cloth appearance [8]. It is known that cloth model can be represented in two dimensional array as shown in Fig. 1. The coordinates from each matrix elements are representing the points of cloth surface. The flexible mesh physical simulation takes into account the elastic spring that joins these nodes. This model presumes that new node positions are generated due to the forces applied to mesh mass-points nodes, to guarantee the required balance among these mass nodes. This approach is common for many cloth animation contributions because meshes are easy to manipulate and efficient to describe deformations as described by Jiang Wang et al. [9]. The interaction between fluid and cloth in real time also draw attention of researcher on studying these interacations [10].

Virtual reality requires several components such as cloth, hair, weapon and etc. The impression of facial expression with emotional aspects determines the believability of virtual human [11]-[17]. Despite the collision detection inside cloth fabrics, other researchers also studied collision avoidance to improve the bevahior of virtual human inside the environment [18]. Tracking the human body was introduced to the science knowledge to provide better interaction using body gesture, voice or speech recognition that known as natural interaction [19], [20]. In addition, markerless tracking enable human to make interactive interaction with real world planar in real time by using gyroscope and inertia sensor [21]-[23].

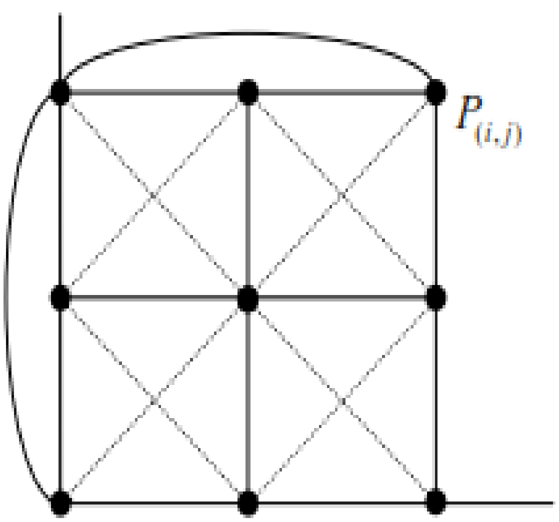

Fig. 1. Mesh strategy for cloth modelling [9].

III. Research Methodology

The process will be started from conducting critical analysis to discuss the important issues of the wet cloth simulation topic. The complete process is reflected at Fig. 2.

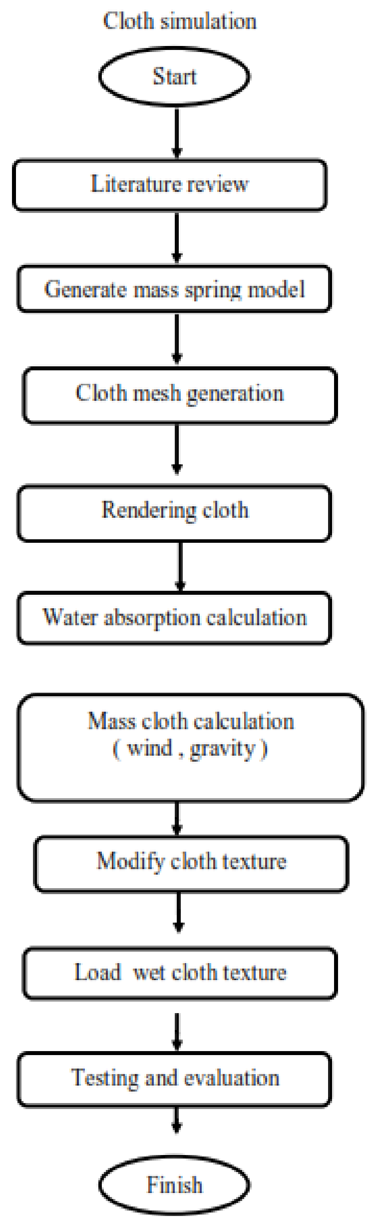

Fig. 2. Methodology.

This stage will explain how to generate textile, which is the first component of functioning simulation of cloth. The method used in this research is famous for its strength and ease of implementation and low cost clothing simulation. It's called Mass Spring Model which uses the idea of masses being linked in mutually style through springs. There are three types of springs used to build the body of textile, bend, stretch and shear. It's called Mass Spring Model which uses the idea of masses being linked in mutually style through springs. Fig. 3 explains the types of springs.

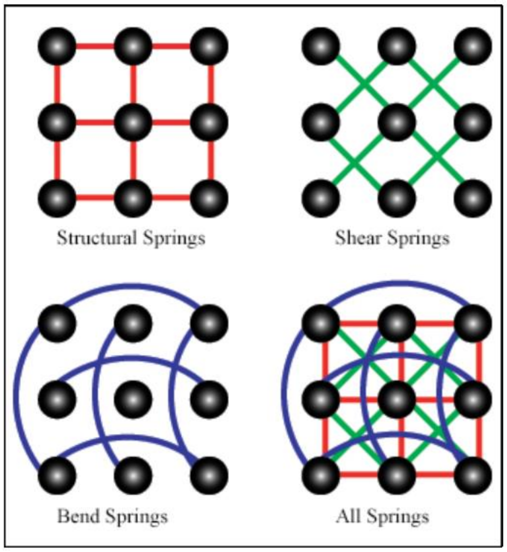

Fig. 3. Types of Spring [24].

A. Cloth Mesh Generation

The flexible form in this work is a net of practical masses every one being coupled to each other by masses springs of extension that didn't have similar value or zero, association among closed mass is grouped in following diverse mode. Fig. 4 shows the process of mesh in the following three steps:

- Mass[i,j] with [i+1,j] then mass[i,j] with[i,j+1] bind to spring known as **mechanical spring.**
- Mass[i,j] with [i+1,j+1] then mass[i+1,j] with[i,j+1] bind to spring known as **shear spring.**
- Mass[i,j] with [i+2,j] then mass[i,j] with[i,j+2] bind to spring known as **flexion spring.**

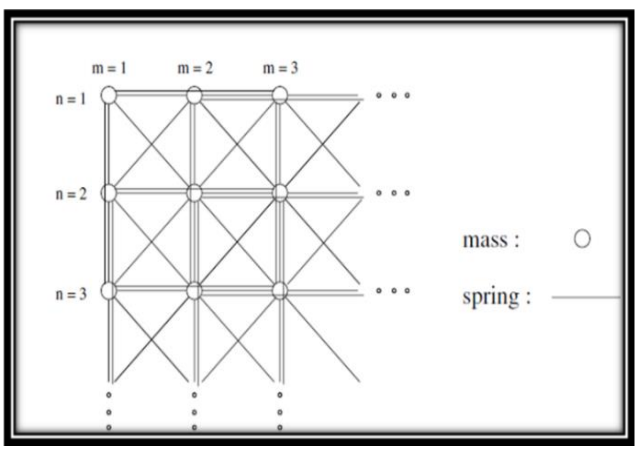

Fig. 4. Mesh between masses and spring [24].

B. Water Absorption Calculation

When cloths are soaked with water, this indicates to get interaction between the water and cloth particles, resulting increasing in the weight of cloths because if attached amount of water in cloth particles. This physical process is nominated as absorption. The quantity of absorbed water is different from cloth type to another. In this work, we will adopt cotton as the basis for calculating the amount of water absorption. Previous researchers calculated absorption amount for water through the satiation, the mass from component in one integration which is computed through (1) [5].

$$m_i = m_i + t\frac{\partial m_i}{\partial t} \tag{1}$$

Where m_i is the weight rate of the mass i at time **t**. In deliquescent modelling investigate; this fluid stream is classically simulated as a dispersal procedure. We study the water imbibition's process and the mass model changing process as following:

$$Q = \partial(1 - e^{-t/a3}) \tag{2}$$

Where Q the amount of water that absorbed through time t. ∂ is the parameter of the weight in soaked case per gram, θ is the hygroscopicity factor constant that possible to be gotten from the fabric component research data, and t is the typical time of the water absorbing process. Ultimately the following equation can be concluded:

$$\frac{\partial m_i}{\partial t} = \frac{\partial Q}{\partial t} = \frac{\partial}{\theta} * e^{-t/10} \tag{3}$$

Each surface of cloth consists of many triangles and forces will affect each triangle on cloth surface as shown in Fig. 5. The wind pressure effect toward cloth is calculated based on algorithm described in Fig. 6.

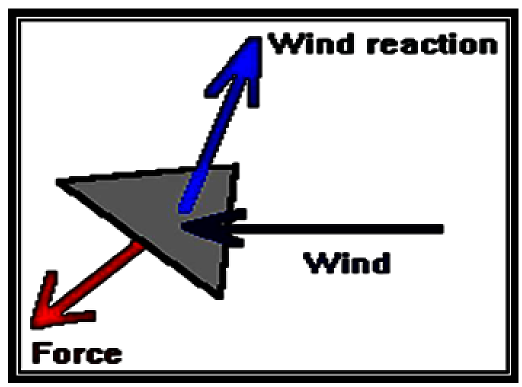

Fig. 5. Force and wind reaction toward cloth surface.

Pseudocode : Calculating wind behavior

```
VECTOR: force
VECTOR: normal
VECTOR: wind
set force vector to (0,0,0) on all points
on cloth
loop through all triangles
force = unitvector(normal) *
dotproduct(normal, wind)
add force to all points making up this
triangle
end of loop
loop through all points on cloth
add gravity to force, add force to
velocity,
end of loop
```

Fig. 6. Pseudo code for wind force calculation.

IV. Result and Discussion

This research is aimed to provide efficient and effective methods of simulating wet cloth and to study the external forces which affect the wet cloth's behaviour, such as wind and gravity forces by using mass spring model. This section explains how to construct the structure of the cloth sheet and describes how to apply the technique that is used to generate the cloth particles. It also displays how to apply wetting model on the cloth in terms of adding fluid to the cloths and how the wetting model will affect the clothes behaviour through changing the mass and the texture colour. The diagram of wet cloth rendering process is described at Fig. 7.

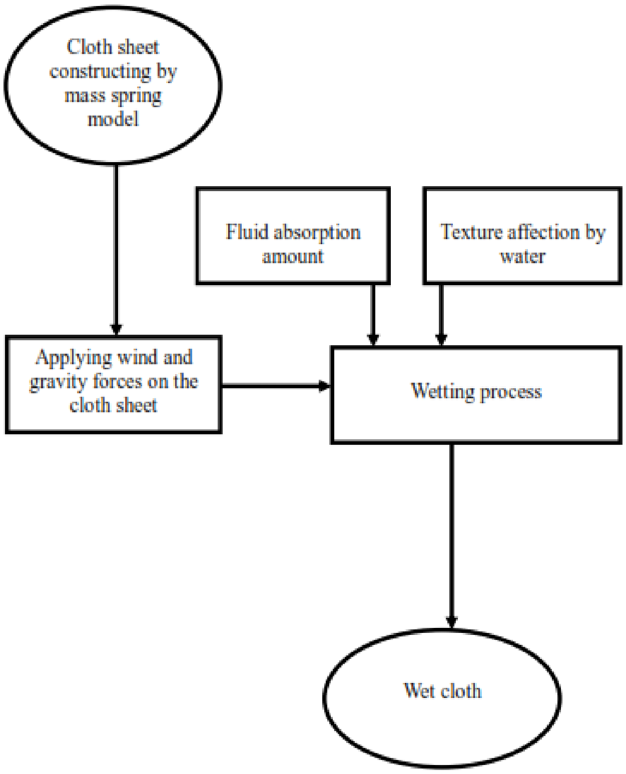

Fig. 7. Flow chart for wet cloth rendering.

A. Mass Spring Model

In 1988 and 1995, Hamann and Parent were the first how introduced Mass spring model. Then, it was further improved by Provo (1995). Mass spring is a technique used in this research to generate clothes patches. In this model the cloth sheet is initialized bya matrix of balls connected by springs. It is one of the most important techniques used widely to simulate cloth in computer graphics applications. The cloth model is embodied through a network of particles of known mass that are linked by a sequence of spring-dampers. The ball in cloth simulation can be described clearly in Fig. 8.

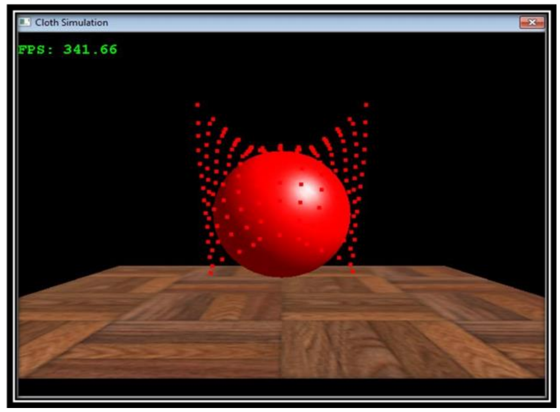

Fig. 8. Clothes ball represented as mass in open GL.

The springs would be the structural aspects of the model and resist the different loads which are put on the particles. Once the simulation is started, each spring's relaxation length is placed towards the original entire spring. The mass values from the contaminants and also the spring constants are based on the consumer. Fig. 9 shows the springs make connection between the balls to create cloth's particles.

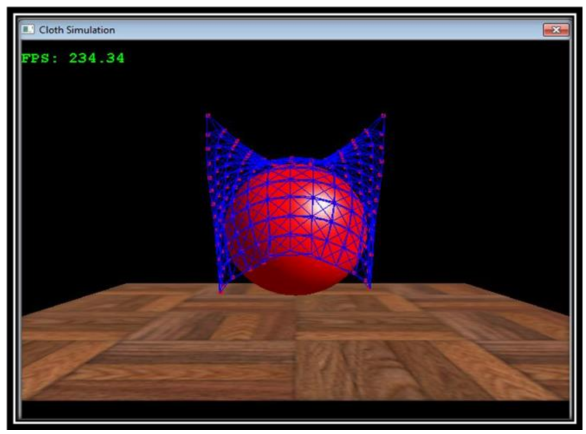

Fig. 9. Interaction between cloth particle in wireframe model with ball.

The masses and springs are set up by Newton's Second Law of Motion. The simulation is advanced incrementally to configuring the cloth sheet. This perspective represents the structure of cloth represented by mesh. Intuitively, this structure will be under the environmental effects that give the cloth properties like the stretching, bending and shearing.

B. Dynamic Forces

In the spring model the cloth is simulated as grid. As explained earlier, the springs connect the nodes while the forces are applied on the nodes to generate an animation. The system is a mesh of $m \times n$ masses. At time t every mass has position Pij (t). Fig. 10 shows the masses as matrix of balls.

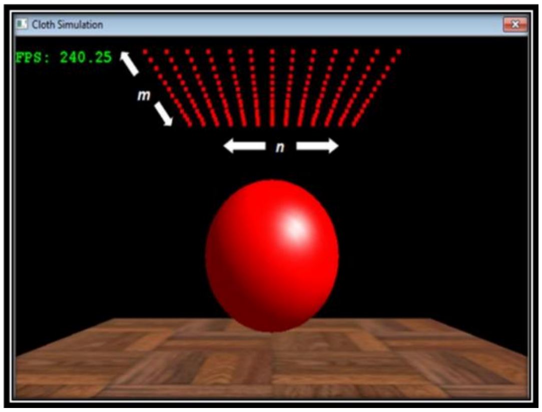

Fig. 10. Mesh of masses m × n.

$$F_{ij} = M_{aij} \tag{4}$$

Where M is the mass at point *Pij (t),* and *aij* is the acceleration caused by the force *Fi,j*. The forces (Fi, j) can be internal and external forces. Internal forces epitomized by the Tensions of interconnected springs, while the external forces will be gravity and wind.

C. Forces Calculation

The basic effect of the internal forces is the Tensions of interconnected springs, which can be calculated by Hock low.

$$F = K \bullet U \tag{5}$$

Where F is the considered force, U is the deformation (change from the essential position) of the flexible body subjected to the force F, and K is the spring constant. The internal force is the resultant of the tensions of the springs linking (Pi,j) to its neighbours.

$$F\ int(P_{i,j}) = -\sum_{k,l} \in \mathrm{R\ K\ i,j,k,l} \left[li,j,k,\mathrm{l} - l^0 i,j,k,\mathrm{l}\ \frac{li,j,k,\mathrm{l}}{|li,j,k,\mathrm{l}|} \right] \tag{6}$$

Where:

- R is the set regrouping all couples (k, l) such as Pk, lis linked by a spring to Pi,j,
- li, j, k,l $= P_{i,j}P_{k,l}$.
- l^0i , j k, l is the natural length of the spring linking Pi , j and $P_{k,l}$.
- $K_{i,j,k,l}$ is the stiffness of the spring linking P*i*,*j* and P*k*,*l*.

Fig. 11 shows the initial position for the springs. When the cloth sheet begin move, springs position and tension value will change.

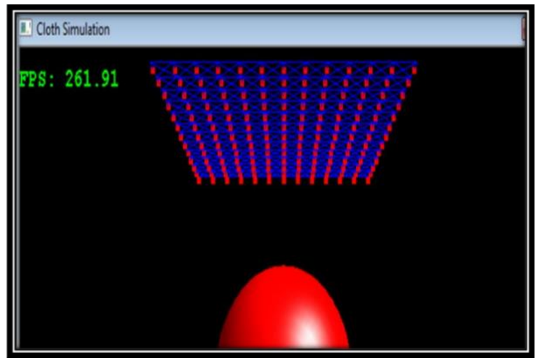

Fig. 11. Spring aspect in the initial positions.

In the initial stage of the springs in mass spring model, the springs are in the neutral length assigned by the user randomly. However, the aspect will be different after applying the internal forces on the springs as shown in Fig. 12.

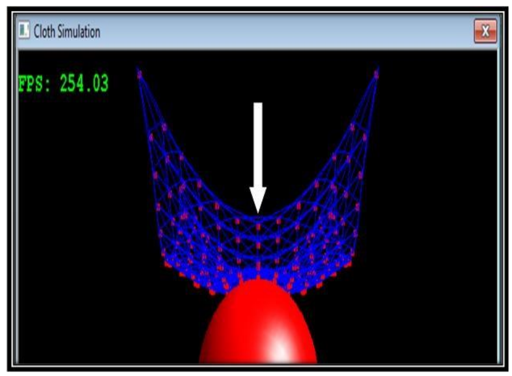

Fig. 12. Spring aspect after deformation.

D. Gravity Forces

The external forces that applied on the cloth sheet in this work are the forces of gravity and wind. The gravity will accelerate the woven cloth toward the bottom, and the wind will change the directions according to the wind resource. Consequently, this work has two different situations (dry, wet). Gravity and wind affect will be applied to change the physical properties in both dry and wet cases. This study work was based on earlier findings on the influence of gravity and wind forces on cloth and the mathematical method which applied to the cloth.

The gravity forces will have effect on the cloth behaviour and physical properties. The impact of gravity forces will increase the speed of cloth landing. In cloth simulation by using mass spring model, gravity influence will be applied on each particle of the cloth. Fig. 13 shows the gravity action on the cloth sheet.

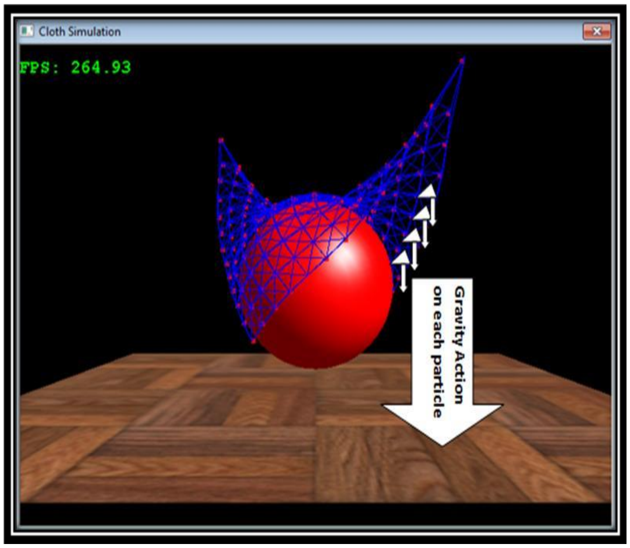

Fig. 13. Gravity forces for each particles.

To calculate the gravity forces acceleration on each of the cloth particle, the following (7) should be applied:

$$F_{gr}\left(P_{ij}\right)=M_{g} \tag{7}$$

Where Fgr (Pij) is the gravity forces for particular point, g is the acceleration of gravity, M is the mass. There are two different scenarios that show the gravity effect in this work. The first scenario will be in case of dry cloth while the second scenario will be in case of wet cloth. In relation to dry cloth, the gravity influence will be less compared to wet cloth because the cloth weight will be in the latter. The different gravity effect in both cases (dry, wet) will be explained and discussed in detail in the evaluation section.

E. Wind Forces

Wind forces in this work are another type of external forces that are applied on the cloth. Wind forces will affect each particle as the gravity forces. The wind influence will be shown according to the wind source. To calculate the wind force, cloth sheet must be broken down into triangles. This process is already done since the cloth is described by array of mass point connected by springs as maintained in the methodology section. Wind forces affection will be calculated for each triangle. By applying variable values to the wind vector, different aspects will be shown in each implementation phase. Different scenarios with different variable values employed in this work to test the wind forces influence on the cloth sheet. Consequently, three values respectively (0.5, 1.0, 1.5) are applied to introduce three aspects of wind force showing the effect of stronger wind every time with higher values. In Fig. 14 (a) wind force value is (0.5) applied on wind vector, the aspect of the cloth affected by the wind forces show the affection is less than (b),(c) scenarios with wind force values 1.0 and 1.5, respectively.

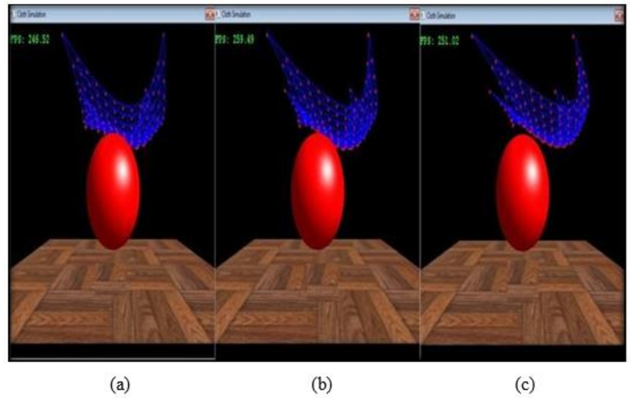

Fig. 14. (a): Cloth with low wind value, (b): Cloth with medium wind value, (c): Cloth with high wind value.

F. Geometric Collision Test

Collision handling is one of the most important steps in cloth simulation. The goal of computer graphics simulations is achieving better image in terms of its similarity to reality. When the garment interacts with the virtual environment, it needs proper handling of the cloth particles collision. In wet cloth simulation of this work, the scenario deals with animated cloth sheet. By using Mass Spring technique the collision can be detected between the cloth points in a very explicit way.

Mass Spring Model is used to simulate cloth animation and collision handling and detection.. If t is inside the current time step, a proximity test is conducted using the position of the points at t. Given points X_1, X_2 X_3, X_4, with velocities V_1, V_2, V_3, V_4, and defining $X_{i,j}$ = Xi− Xj, the time t when the points will be coplanar are the roots of the cubic (8).

$$(X_{2,1}+tv_{2,1})\times(x_{3,1}+tv_{3,1})\cdot(x_{4,1}+tv_{4,1})=0 \tag{8}$$

G. Fluid Absorption

This section describes the cloth wetting model, and explains how the interaction occurs between the fluid and cloth particles in steps. In which the cloth wetting is a result for several physical actions, such as weight increments, color changes and thus different behaviors. This work shows how the coupling between the cloths sheet, which is considered as cotton, and the fluid, which is considered as water. The wetting model will be summarized by three steps. First is the cloth absorption of the water, second is the texture affection after getting wet and finally the behavior and rendering.

The absorption applied in this work through testing different values reaching to the saturation level where there is no more absorption. Saturation level extracted from [5] work by physical experiment applied on different types of clothes. Table 1 covers the experiment of [5]. This experiment has been done on three type of cloth which is cotton, coarse wool and high absorption fabric. Cotton absorption value of [5] experiment which is 0.84 considered as the standard value for the current work.

TABLE I. FABRICS PARAMETER OF ABSORPTION[5]

Parameters	Cotton(g/m^2)	Coarse wool(g/m^2)	High absorption Fabric(g/m^2)
θ	0.84	1.24	2.492
a3	8.844	4.8936	3.3803

TABLE II. MASSES VALUES FOR THE CLOTH PARTICLES DURING WETTING PROCESS

Time in (second)	Original Mass in (gram)	Mass after wetting in (gram)
1	0.01	0.093
2	0.093	0.176
3	0.176	0.259
4	0.259	0.342
5	0.342	0.425
6	0.425	0.508
7	0.508	0.591
8	0.591	0.674
9	0.674	0.757
10	0.757	0.84

Absorptions values applied through particular time, every time the mass increases with the same value of gravity. The mass modification simulates wet cloth and makes it in the saturation level implemented into 10 phases of the cloth particles masses. Table 2 describes the experiment values where, the initial cloth particles mass referred as the original mass and the cloth particles after effect by the fluid referred as after wetting mass. Table 2 describes the mass change during 10 second period of simulation.

When the cloth particles interact with fluid, the particles mass will increase until arrive to the saturation level. Fig. 16. represents the resulted cloth in saturation situation. When the cloth particle arrives to the fullness, cloth particles will not absorb and not effected and the cloth texture changed to the darkest color. Fig. 15 refers to the saturated cloth where, the cloth sheet had effected by the fluid and the cloth texture changed to the darkest color. Also the tension forces between the springs are affected by the new masses. The springs which connect between the particles are stretched as clarified in Fig. 15.

Fig. 15. Cloth in saturation mode.

H. Texture Change after Wetting Process

The texture color in cloth simulation reflects the real scene, where if cloth sheet is dry the texture color should be natural, and if the cloth sheet is wet the color will be darker as proofed in a previous research [5]. Wet cloth in this work was given concentrations of the texture color according to the absorption amount during 10 seconds of time. The color concentration increases to darker by increasing the absorption amount until reaching the moistened color completely. Fig. 16. describes the changes in the cloth texture color according to the wetting amount. The first scenario shows the texture with low concentration while the second and third scenarios refer to the texture after increasing the wetting amount. The color goes darker comparing with the first scenario. Finally, the fourth scenario represents the cloth texture in saturation case where the color has reached the highest concentration.

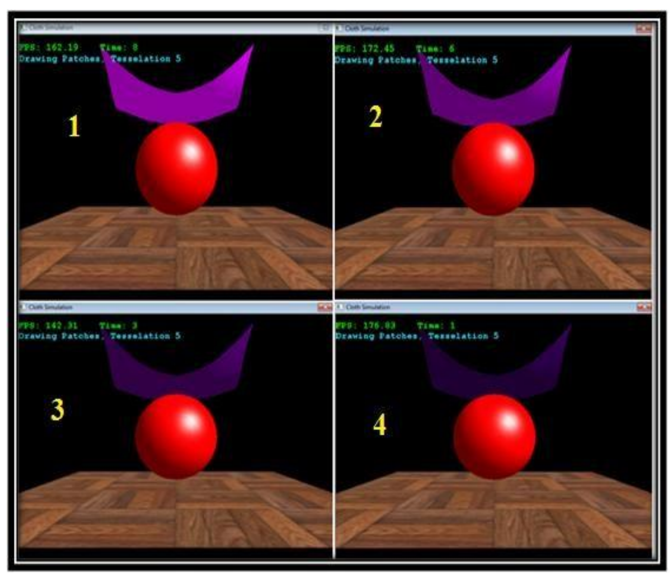

Fig. 16. Cloth texture change from dry to wet.

I. Evaluation

The first test in FPS has been done to the dry cloth to show the difference between the frames dry cloth case. Fig. 17 clarifies the dry cloth frames as extracted from the FPS where, the frames were measured according to the time in second. The trend shows that there was a significant increment of mass since starting of rendering then slowly dropped in the following time.

After applying the wetting model, the FPS measurements were affected by the variation of the physical properties which were added through new frames. Because of the variables scenarios applied to check the behavior after every time of masses changes considerations with the gravity, many tests should be applied to show the FPS for those scenarios. The first test was done on the first wetting value as shown in Fig. 18, where the mass has been increased by 0.093g which was obtained from the experiment values [5] which are mentioned in Table 2. Wet cloth frames were tested by applying 4 different values of masses changing in the wetting experiment. The values were taken from Table 2 as the (first is 0.093g, fourth is 0.342g, seventh is 0.591g and tenth is 0.84g).

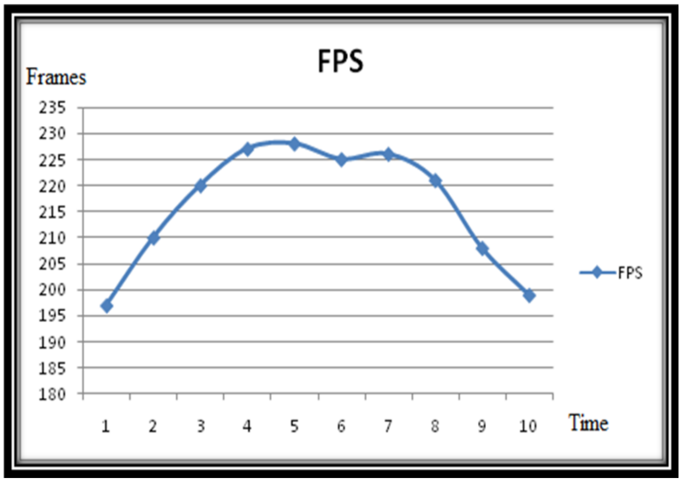

Fig. 17. FPS for dry cloth rendering.

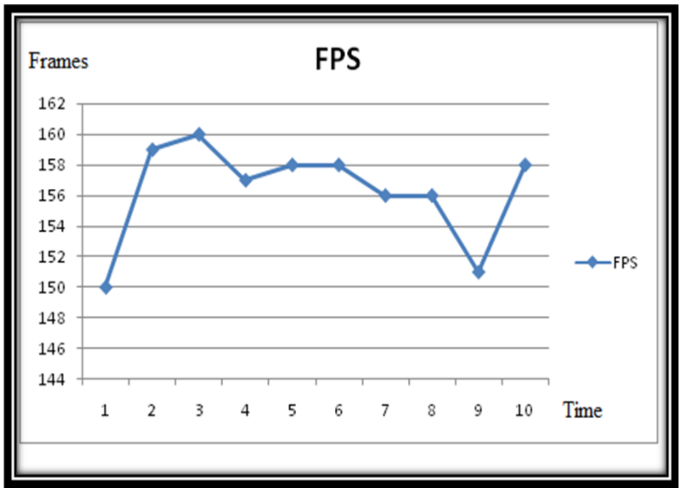

Fig. 18. FPS for wet cloth rendering.

In wet cloth simulation, the cloth in natural situation spent 4 second to arrive the floor, while the wet cloth in saturation situation spent 2 second to arrive at the same destination. Therefore, saturated cloth requires half the time compared to dry cloth time during simulation. Wet cloth behavior is shown clearly in Fig. 19. Cloth appearance also seems different due to the affection of the fluid on the cloth. Fig. 20 shows that FPS increased rapidly at the beginning of rendering then dropped slightly and stayed steady for a period of time. At the end of rendering time, FPS dropped then rose up again. This rapid change was to the mass change of each element of cloth.

The second test conducted in this work was the behavior test. The difference between dry and wet cloth has some views like the external appearance, the physical properties and the behavior mainly when an animation occurs. There were two tests conducted to show different behaviors.

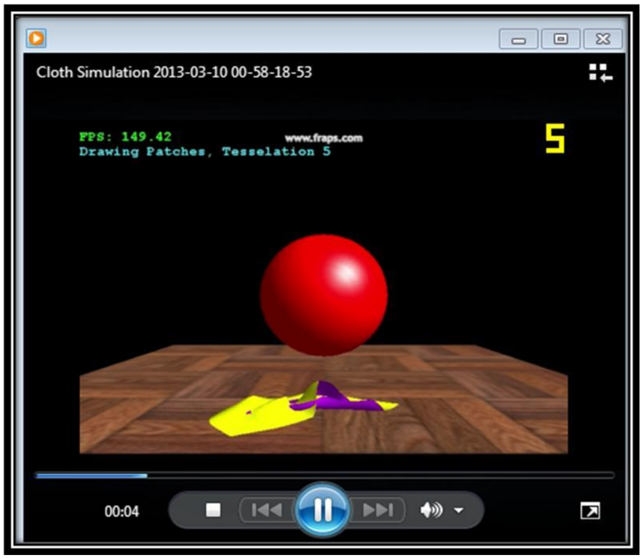

Fig. 19. Dry Cloth simulation in physical test.

Fig. 20. Wet Cloth simulation in physical test.

The first presented the dry cloth behavior and the presented the wet cloth. The aims of these tests were computing the time of cloth sheet arriving to the floor. The wet cloth should be faster due to the heavier weight. Fig. 20 presents the first test for the dry cloth by showing the cloth view during the moment of its arrival to the experimental environment floor.

V. Conclusion

This work presents an approach for simulating cloth affected by internal and external forces. Mass spring model was used to simulate cloth. It gave high flexibility to change or modify the garment properties. Also it enabled cloth particle to deal smoothly with the external influences that could affect the simulation process, Mass Spring model also was shown as a credible approach to simulate wet cloth. Furthermore this model also showed agreeable method to simulate the forces influence especially when there is an animation.

The study was conducted to achieve two goals. First goal has been achieved by introducing the wet/dry cloth simulation technique starting by cloth structuring, fluid absorbing, texture color transformation and wet/dry cloth behavior in term of animation and appearance. Second goal has been achieved by simulating the forces action and its effect on cloth appearance. The realization of mass spring under the external forces of wind and gravity technique was successfully done in it was done with wet and dry cloth simulation. The technique had sufficient ability to give graceful aspect of high realism and obviousness wet/dry cloth simulation. This technique can show clearly the influence of the external forces like gravity and wind in cloth simulation.

This work also showed the cloth affection by absorbing different values of fluid can give variables wet cloth simulation aspects. During cloth wetting process handling, textures color transformation has been described clearly. Wetting technique explained the relation between textures color and the weigh modification. Where, the experiment proved that the cloth surface color converts to darkness during the absorption process stages. The experiment showed that, in the saturation level, the cloth texture color was in the darker concentration and the texture did not change after reaching the saturation. Finally evolution proved that the wet cloth has different behavior from the dry cloth in term of animation. The experiment of behavior indicated that the dropping rate is double the time faster than dry cloth. In other words, the wet cloth needs half the time of the dry cloth to arrive to the floor. The future work is handling the wet cloth simulation with self-collision detection for virtual human, where the wrinkle effects are created and self-collision detection need to be computed in complete ways.

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