International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-10 Issue-3, September 2021

Real-Time Cloth Simulation for Hula Costume CAD Development

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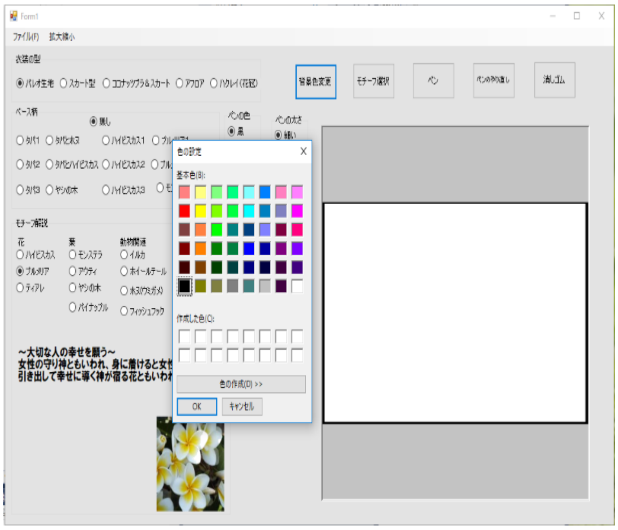
Abstract*: *In recent years, 3D computer graphics (3DCG) technology has been applied in various fields such as AR technology, VR technology, movies, games, and virtual fitting of clothes. Among them, there is the problem of contact between clothing and other objects (such as the body). In this paper, we focus on that problem. Since this research is part of the development of CAD for the design of hula costumes, and since we assume that the users of the CAD will have PCs with not very high performance, we took an approach that does not require a large amount of computation. As a representation of the cloth, we used a mass-spring model in which springs and mass points are connected in a grid. We also compared how the three methods of calculating position and velocity, Euler method, FB Euler method, and Runge-Kutta method, affect the simulation results.

Keywords*: *Cloth Simulation, Collision Detection, Computer Graphics, Mass-Spring Model

I. INTRODUCTION

In this research, as a part of the CAD development of hula costumes as shown in Fig. 1, we simulate the cloth applied to 3DCG animation using a physical model, and detect the collision between the human body model of a hula dancer dancing in 3DCG and the pou skirt worn, so that the costume does not penetrate the body. Fig. 1 shows the completed CAD system. In this study, we investigated a method to avoid inconsistencies such as the costume penetrating the body. This research is based on our previous work on the simulation of the skirt), which is represented by a cylindrical model that takes into account the contact with the lower body represented by the cylindrical shape in Fig. 2 [1]. Fig. 2 shows the results of running previous studies.



～大切な人の幸せを願う～
女性の守り神ともいわれ、身に着けると女性
引き出して幸せに導く神が宿る花ともいわれ

Fig. 1: Example of completed CAD

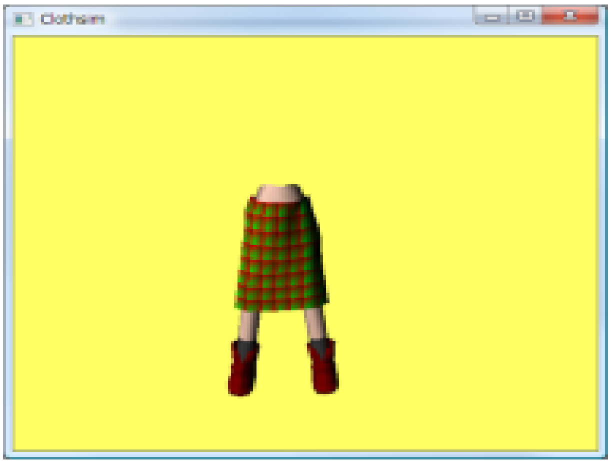


Fig. 2: Conventional execution result [1]

II. RESEACH BACKGROUND

Miyazaki Prefecture has a large hula population, probably due to its similarity to Hawaii in mythology and climate. On the other hand, many hula costumes are handmade, and it costs tens of thousands of yen to produce an original design. Therefore, we are developing a CAD system for hula costumes, based on the idea that the use of a design CAD system can reduce the economic burden. We also envision that the CAD can be used on an ordinary PC that does not have high performance. In this paper, we are conducting a basic research to confirm the behavior of cloth when danced after designing a costume by using 3DCG animation. It should be noted that although there are examples of research on regular apparel CAD, there is no precedent specific to hula costumes [2], [3].

Manuscript received on September 02, 2021.
Revised Manuscript received on September 08, 2021.
Manuscript published on September 30, 2021.

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III. MASS-SPRING MODEL

In this study, a physical model called the mass-spring model was used to represent the cloth. In this model, springs and mass points are connected in a grid pattern as shown in Fig. 3, which is a commonly used model to represent cloth in 3DCG. This model is used to represent the four properties of weight in addition to tensile, shear, and bending in Fig 4, with the mass points [4]. These properties are represented by a structural spring connecting between adjacent mass points in Fig 5 for pull, a shear spring connecting between diagonally located mass points for shear, and a bending spring connecting between two adjacent mass points for bending. Note that the springs are represented by a simplified version based on Hooke's law.

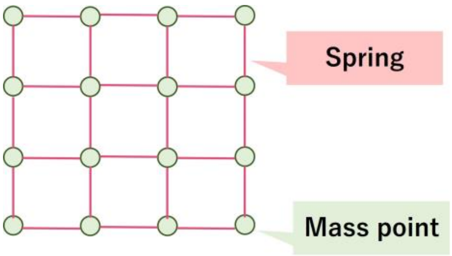

Fig. 3: Mass-spring model [1]

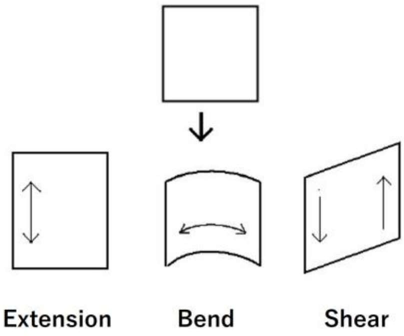

Fig. 4: Mechanical properties of cloth [1]

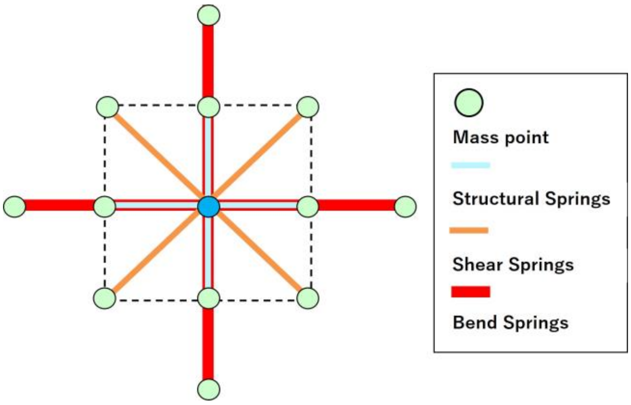

Fig. 5: Structure of the mass-spring model

IV. FORCE ON THE MASS POINTS

The elastic force of the spring shown in Fig. 6, gravity, resistive forces such as air resistance and damping force, and wind force are considered as forces applied to the mass-spring model's mass points.

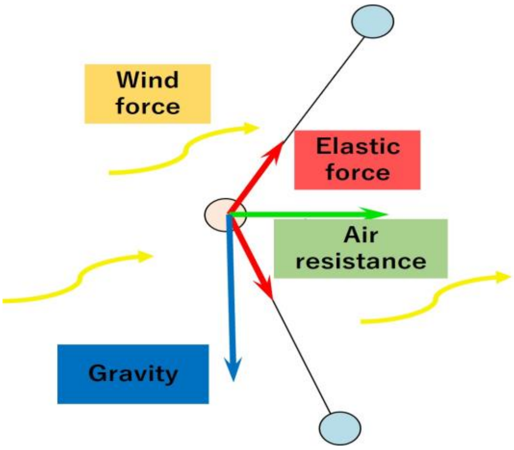

Fig. 6: Force applied to a quality point

First, the elastic force of the spring is defined as $P_{ij} = P_j - P_i$, where the coordinates of mass points i and j are $P_i(x_i, y_i, z_i)$ and $P_j(x_j, y_j, z_j)$, respectively. Here, the force $f_{stretch}$ exerted by mass point j on mass point i is expressed by the following equation

$$f_{stretch} = k(|P_{ij}| - L)\frac{P_{ij}}{|P_{ij}|} \qquad (1)$$

Where, L is the natural length of the spring and k is the spring constant. The gravity applied to the mass point i is expressed by the following equation

$$f_{gravity} = m_i g \qquad (2)$$

where m_i is the mass on the mass point i and g is the acceleration of gravity. Gravity and elastic force alone will cause the spring to oscillate permanently because of the law of conservation of energy. Therefore, a force is added to dampen the force of the spring. The resistance force is expressed by the following equation, where v_i is the velocity of the mass point i and ρ is the resistance coefficient.

$$f_{damper} = -\rho v_i \qquad (3)$$

In this study, wind force is also added to the force on the mass point to reproduce the skirt fluttering in the wind during the simulation. The wind force is assumed to be applied to the mass point as a force in the x-axis and z-axis directions in 3D space.

$$f_{wind} = \alpha(\cos(\beta)\sin(\gamma) + \sin(\beta)\sin(\gamma)) \qquad (4)$$

where α is an arbitrary constant and t is a certain time, β and γ are set to the values in the following equation.

$$\beta = \frac{100t}{10} \qquad \gamma = \frac{100t}{15} \qquad (5)$$

From the above, the force applied to a certain mass point i at a certain time t can be expressed as follows.

$$F_i(t) = f_{gravity} + f_{damper} + f_{stretch} + f_{wind} \tag{6}$$

The acceleration $a_i(t)$ of mass point i at a certain time t can be expressed by the following equation based on the equation of motion using $F_i(t)$ in (6).

$$a_i(t) = \frac{1}{m_i} F_i(t) \tag{7}$$

The velocity $v_i(t+\Delta t)$ and position $x_i(t+\Delta t)$ of the mass point i when Δt time has elapsed from a certain time t are obtained by Euler's method, FB Euler's method, or Runge-Kutta's method. The first Euler's method is expressed by the following equation using $a_i(t)$ in (7).

$$\begin{aligned} x_i(t+\Delta t) &= x_i(t) + v_i(t)\Delta t \\ v_i(t+\Delta t) &= v_i(t) + a_i(t)\Delta t \end{aligned} \tag{8}$$

The second, FB Euler method, is a calculation method that uses the Euler method for the current acceleration when calculating velocity, and applies the backward Euler method to the velocity at time $t+\Delta t$ when calculating position.

$$\begin{aligned} v_i(t+\Delta t) &= v_i(t) + a_i(t)\Delta t \\ x_i(t+\Delta t) &= x_i(t) + v_i(t+\Delta t)\Delta t \end{aligned} \tag{9}$$

The third Runge-Kutta method is calculated by the following equation, where c is the coefficient and g is the acceleration of gravity.

$$\begin{aligned} kv_1 &= a_1\Delta t \\ kx_1 &= v(t)\Delta t \\ a_2 &= \frac{F(x(t)+kx_1/2)}{m} - cv(t) + g \\ kv_2 &= a_2\Delta t \\ kx_2 &= (v(t)+kv_1/2)\Delta t \\ a_3 &= \frac{F(x(t)+kx_2/2)}{m} - cv(t) + g \\ kv_3 &= a_3\Delta t \\ kx_3 &= (v(t)+kv_2/2)\Delta t \\ a_4 &= \frac{F(x(t)+kx_3/2)}{m} - cv(t) + g \\ kv_4 &= a_4\Delta t \\ kx_4 &= (v(t)+kv_3/2)\Delta t \\ v(t+\Delta t) &= v(t) + \frac{1}{6}(kv_1 + 2kv_2 + 2kv_3 + kv_4) \\ x(t+\Delta t) &= x(t) + \frac{1}{6}(kx_1 + 2kx_2 + 2kx_3 + kx_4) \end{aligned} \tag{10}$$

The above equation was used to represent the behavior of the cloth.

V. COLLISION DETECTION BETWEEN BODY AND MASS POINT

In this study, we changed from the previous simple human body model of the lower body represented by the cylindrical shape in Fig. 7 to a realistic human body model as shown in Fig. 8. In this study, we used 13 capsule shapes arranged in consideration of the unevenness of the lower body in Fig. 8 as collision targets for the mass points of the cloth.

Fig. 7: Conventional human body model

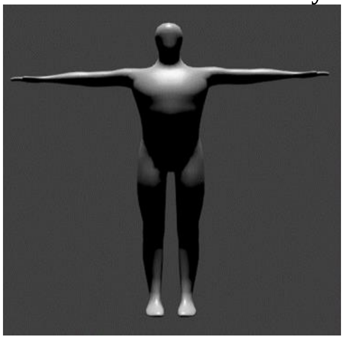

Fig. 8: Human body model used in this study

In this study, 13 capsule shapes were used to detect the collision with the skirt, considering that the position of the cylinder can correctly determine the collision and the processing speed is not too slow. The central axis of the cylinder was placed at the green rectangle in Fig. 9, the radius of the cylinder was set from the central axis, and hemispheres of that radius were placed at both ends of the cylinder to form the capsule shape.

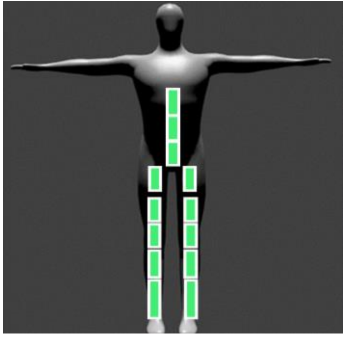

Fig. 9: Position of the central axis of the cylinder

The collision between the capsule and the mass-spring model is detected by dividing the capsule into a cylindrical part and a hemispherical part. First of all, the intersection of the vertical line from the mass point x to the line segment ab of the central axis of the cylinder and the line segment ab is defined as point y. This can be expressed by the following equation.

$$\begin{aligned} y &= a + s(b-a) \\ (y-x)\cdot(b-a) &= 0 \end{aligned} \tag{11}$$

where s is a scalar.

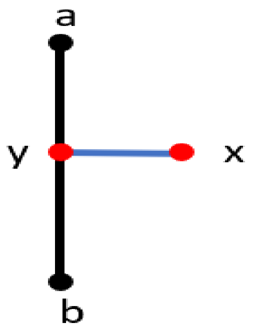

Fig. 10: State of Equation (11)

When the radius of the cylinder part is r and the distance between the mass point x and the point y is r', the cylinder part and the mass point x are said to collide when the following (12) is true.

$$r' - r < 0 \tag{12}$$

Equation (12) is shown in Fig 11. Fig 11 is a cross-sectional view of a cylinder.

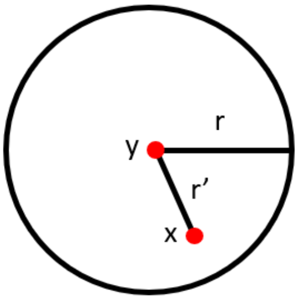

Fig. 11: State of Equation (12)

If (12) does not hold, the next step is to detect the collision between the hemisphere part of the capsule shape and the mass point x. The radius of the hemisphere is r, just like the column. The center point of the hemisphere is either a or b. The distance between a (or b) and the mass point x is r''. Suppose that the hemisphere part and the mass point x are in collision when (13) holds.

$$r'' - r < 0 \tag{13}$$

(13) is shown in Fig 12. Fig 12 is a cross-sectional view of the hemisphere.

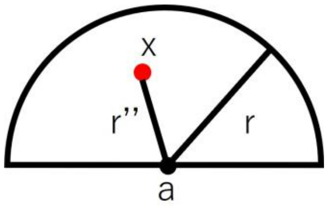

Fig. 12: State of Equation (13)

In the above process, if the body and the mass point have collided, the post-collision behavior is calculated.

VI. CALCULATION OF POST-COLLISION BEHAVIOR

The penalty method is used to calculate the behavior after a collision. The penalty method is one of the rigid body simulation methods. When objects collide with each other and run into each other, a force proportional to the run-in value (penalty force) is applied to obtain the behavior after the collision [5]. The characteristics of the penalty method are that the amount of calculation per step is small, making it suitable for parallel real-time simulation, and that friction and bounce coefficients can be easily modeled. In this study, the penalty method is utilized because it can be achieved by introducing a spring between the surface of the cylinder and the mass point that has invaded the cylinder, and because it is designed to take a simple calculation method. These allow us to use the force of the spring to push back against the grid points that are colliding with the cloth, out of the foot so that they do not get stuck in the foot. When the penetration is d and the relative velocity between objects is $\dot{d}$, the spring constant is k and the positive proportional constant is b, the penalty force is expressed by the following equation.

$$f_{penalty} = kd + b\dot{d} \tag{14}$$

The force $f_{penalty}$ in (15) bounces the intruding mass point outward.

VII. RESULT AND DISCUSSION

In this study, C++ programming language was used as the programming language, Intel(R) Core™ i7-7700 3.60GHz CPU, 16GB RAM, and DirectX9 was used as the CG library. The execution results of the Euler method, FB Euler method, and Runge-Kutta method to calculate the position and velocity are shown in Fig. 13, Fig. 14, and Fig. 15, respectively.

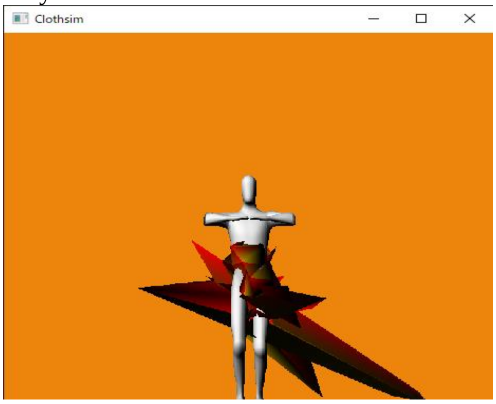

Fig. 13: Results of Euler method run

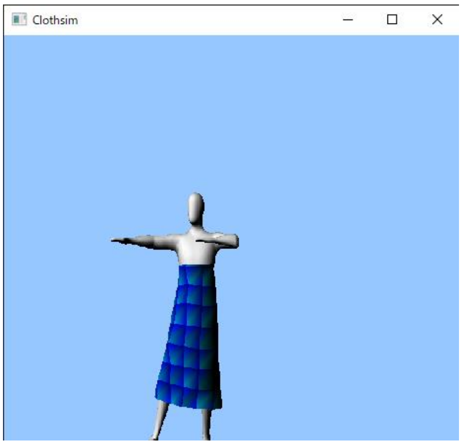

Fig. 14: Results of FB Euler method run

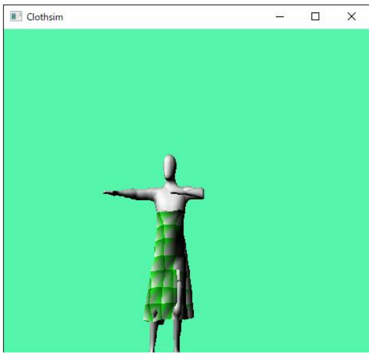

Fig. 15: Results of Runge-Kutta method run.

From Fig. 13, the results of running the Euler method resulted in the skirt flying away from the body, but the movement of the human model did not slow down. This result may be due to the divergence of the solution in the calculation of the position and velocity of the cloth. The results of the FB Euler method in Fig. 14 were stable, but the movement of the human model slowed down due to the large number of calculation processes. The results of the Runge-Kutta method shown in Fig. 15 showed that the skirt penetrated the legs and the movement of the human model was the slowest among the three calculation methods. The reason may be that the Runge-Kutta method has the largest amount of calculation among the three calculation methods. The reason why the skirt penetrated the leg could be that the position of the mass point was not calculated correctly and the behavior after the collision was not calculated correctly.

VIII. CONCLUSION

In this study, we implemented the method in 3DCG such that there is no inconsistency in the expression when the paw skirt collides with the body. Since the results of this study showed the most ideal results when the FB Euler method was used as the calculation method for position and velocity, we would like to use the FB Euler method as the calculation method to improve our study. In addition, we have not yet decided on a plan to improve the processing speed. As for other visual issues, we would like to express the differences in cloth materials and patterns by changing the texture mapping and parameters of the mass-spring model, to implement hula costumes other than skirts, and to make the human model wear traditional Hawaiian accessories such as leis and bracelets. These are just a few examples. In addition, including the improvement measures mentioned above, we would like to make efforts to create a CAD system that can simulate the various movements of the hula dance, to express the cloth more realistically, and to make the research more practical.

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