Cloth Simulation with Adaptive Force Model in Three-Dimensional Space

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ABSTRACT
An adaptive force model is proposed to achieve better performance between the accuracy and the speed of cloth simulation in three-dimensional (3D) space. The proposed force model can be expressed with a general mathematical form demonstrated by the distance between the clothing and the human body. This paper defines how a continuous adaptive area can be established with a shape "block". It is clarified that, within a specific block, a force model is expressed with the gravity of the clothing, the forces of the adjacent blocks and the anti-force of the human body to the block. In this manner, the force model of the desired clothing can be obtained through a general mathematical expression. The simulations and experimental results demonstrate that the acceptable clothing simulation in 3D space can be achieved with higher speed by saving about 20.2% runtime, and the efficiency of the proposed scheme can be verified.

Keywords: Garment simulation, Force model, General expression, block

INTRODUCTION
Clothing simulation in three-dimensional (3D) space has become increasingly popular in the fields of virtual reality (VR) related to the clothing design, clothing demonstration and computer animation, etc. In addition, along with the development of the internet, applications such as virtual try-on of clothing and 3D games require that efficient and highly accurate models simulate clothing at speeds as high as possible.

In general, clothing simulation can be cataloged into two different types: micro and macro clothing simulation. Micro clothing simulation refers to a demonstration of clothing by simulating the physical characteristics of the internal structures in the yarns [1-3]. Macro clothing simulation neglects the internal physical structures and shows the characteristics of the relationship between the clothing and the human body. This paper proposes the macro clothing simulation plan.

Many researchers have developed different methods to simulate macro clothing. Provot proposed a mass spring model which describes the relationship between the clothing and the human body [4-7]. This method applies Hooke's Law and can be described with an equation in Newton's Second Law. In solving an equation concerning the above statement, the position and velocity of the mass can be computed. In this model, the spring is assumed to be linear. This influences the accuracy of the simulation when over-stretching of the spring occurs. Baraff and Witkin simulated clothing by triangulated surfaces, which is expressed by stretching and shear deformation [8-9]. Subsequently, stable simulation can be obtained by applying a numerical solution via a semi-implicit integral method. Choi proposed the immediate Buckling Model based on the Baraff's method [10], which demonstrates abundant folds of the clothing with high accuracy. However, this model requires more computation that fails to meet the requirements of clothing simulation in real-time. Terzopoulos put forward a continuum elastic deformation model derived from Newton's Law and theory of elasticity [11]. Displacement of the desired clothing can be calculated by solving an equation describing the position of the clothing in space. Aono described the clothing simulation as a problem based on a balanced equation consisting of elastic theory and dynamics principles, with which the parameters can be computed to improve the fidelity of the simulation [12]. Carigan improved Terzopoulos' method by putting forward a continuum elastic deformation model, but the computation of the algorithm is so complicated that it can hardly be used for real-time simulation [13]. Thalmann developed a novel method to improve the accuracy of clothing simulation at the cost of longer simulation time [14-15]. Kang simulated geometrical and physical methods for clothing combing [16-17]. The proposed method uses physical methods to obtain key parameters. Then, geometrical methods are used to calculate the nodes using the cubic spline interpolation based on the determined key parameters. This method speeds up the simulation, but the effectiveness decreases accordingly. Cordier divided clothing into three types using a hybrid model: tight, loose and floating clothes [18]. Different types are related to different models. This method improves the accuracy of the simulation to some extent. Jian Dong Yang solved the corresponding equations with fourth-order Runge-Kutta method [19]. However, the inherent high computation of the fourth-order Runge-Kutta method is still not solved. Chuan Zhou focused on an algorithm for the folding of clothing simulation using a mass-spring model [20]. Matthias Muller provided a method named position based dynamic, which performs according to the position of the vertex of the clothing. It analyzes gravity while ignoring other forces [21]. Apart from gravity, this method does not demonstrate the fold of the clothing in detail due to the absence of other forces. In order to simulate clothing, Dongyong Zhu segmented the human body into different segmentation models and demonstrated it requires more computation [22].

In summary of macro clothing simulation, the above methods require more computation because of different equations involved. They introduce negative effects into the development of clothing simulation in real-time situation such as virtual try-on via the internet.

This paper proposes an adaptive force model in 3D space based on the distance between the desired clothing and the human body to alleviate the problem. The distance is expressed in a general mathematical form. Unlike conventional methods [18, 22], the proposed plan should not classify the segmentation of clothing according to the human body in advance. The distance can be determined by the lower and upper range in the proposed general expression. With the distance, a force model in 3D space is also derived considering all possible forces including gravity, which can be beneficial to demonstration of the folding of the clothing. Using the force model, the displacement along each axis in 3D space can be computed. In this manner, the deformation of the clothing on the human can be demonstrated. By adjusting the corresponding parameters, a faster and more accurate simulation can be achieved. Experimental results confirm the efficiency of the proposed scheme.

MODEL AND ALGORITHM

As claimed above, the proposed scheme in this paper aims to demonstrate a more accurate and faster simulation in 3D space. This method is performed in different steps. A derivation of a general mathematical expression for the distance between the clothing and the human body should be determined. For clarity, a concept 'block' is defined by referring to the continuous area. A block can be formulated as a force model expressed with a general mathematical form considering all possible forces including gravity and other forces within it. By solving the force model of the block, the displacement of the clothing simulation can be computed so a demonstration of clothing deformation in 3D space can be formed. In the end, the corresponding parameters in the general expression can be slightly adjusted until optimum performance is obtained.

For further clarity, some symbols are defined in *Table I*.

Block Determination

In order to obtain improved accuracy speed of the simulation, a “block” is defined in this paper. This indicates a continuous area which represents the distance between the clothing and the human body. To be specific, for the kth block, the corresponding set S_k can be expressed by Eq. (1), where k represents the index of a block, $\|\cdot\|_2$ denotes 2-norm, $V_L^{(k)}$ is the predefined value for the lower range and $V_H^{(k)}$ is for the upper range, respectively.

$$V_L^{(k)} \leq \arg_{S_k} \min_{(x,y,z)\subset S_k} \| p(x,y,z) - q(x,y,z) \|_2 \leq V_H^{(k)} \tag{1}$$

From Eq. (1), one can clearly see that the size of the kth block can be increased and decreased by adjusting the lower range value and the upper range value $V_H^{(k)}$. For example, by increasing the upper value $V_H^{(k)}$ or decreasing the lower value $V_L^{(k)}$, the continuous area of the kth block can be expanded. As a result, the simulation can speed up while the accuracy of the simulation decreases accordingly. In this manner, a better balance between the accuracy and the speed of the simulation can be achieved by presetting the parameters $V_L^{(k)}$ and $V_H^{(k)}$.

TABLE I. Symbols and Description.

Symbols	Description
$g_f(x,y,z)$	Mass density of the clothing
$q_f(x,y,z)$	Force density of the human body on the clothing
$p_f(x,y,z)$	Internal line force coefficient of the clothing
$q(x,y,z)$	Curved surface equation of the human body
$p(x,y,z)$	Curved surface equation of the clothing

Force Model of a Block

In general, a block can be modeled in 3D space as depicted in *Figure 1*, where the z-axis is in the opposite direction of gravity, and the x-axis and y-axis constitute a plane perpendicular to z-axis.

For discussion purposes, a block has the same displacement along a given axis, that is, $\Delta x^{(k)}$ represents the displacement of the kth block along the x-axis, $\Delta y^{(k)}$ and $\Delta z^{(k)}$ denote the displacements along $y-$ and z-axis. A curve as an equation describing the boundary in the kth block is written as $p^{(k)}(x,y,z)$ derived from the curved surface equation of the clothing $p(x,y,z)$ in *Table I*. The curved surface equation of the human body in the kth block is expressed with the symbol $q^{(k)}(x,y,z)$, which is identical to the expression $q(x,y,z)$ where the coordinate pair (x,y,z) is in the set S_k from Eq. (1).

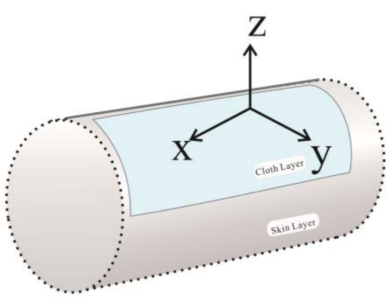

FIGURE 1. Force model in 3D space.

From the curved surface of the human body $q(x,y,z)$, the normal vector of the surface $\mathbf{e}_q$ can be computed based on Eq. (2).

$$\mathbf{e}_q = (\frac{\partial q}{\partial x}, \frac{\partial q}{\partial y}, \frac{\partial q}{\partial z}) \quad (2)$$

Subsequently, the angles of the vector $\mathbf{e}_q$ along the $x-$, $y-$ and $z-$ axes, that is, α_q, β_q and γ_q, can be obtained using Eq. (3).

$$\begin{aligned} \alpha_q &= \arccos(\frac{\partial q / \partial x}{\| e_q \|_2}) \\ \beta_q &= \arccos(\frac{\partial q / \partial y}{\| e_q \|_2}) \\ \gamma_q &= \arccos(\frac{\partial q / \partial z}{\| e_q \|_2}) \end{aligned} \quad (3)$$

Similarly from the curved surface of the clothing $p(x,y,z)$, the normal vector of the surface, $\mathbf{e}_p$, and the corresponding angles along three axes, α_p, β_p and γ_p, can be determined using Eq. (4).

$$\begin{aligned} \mathbf{e}_p &= (\frac{\partial p}{\partial x}, \frac{\partial p}{\partial y}, \frac{\partial p}{\partial z}) \\ \alpha_p &= \arccos(\frac{\partial p / \partial x}{\| e_p \|_2}) \\ \beta_p &= \arccos(\frac{\partial p / \partial y}{\| e_p \|_2}) \\ \gamma_p &= \arccos(\frac{\partial p / \partial z}{\| e_p \|_2}) \end{aligned} \quad (4)$$

To maintain the balance of force along $z-$axis, Eq. (5) can be deduced for the kth block with set S_k, where g is the gravity constant $g = 9.8N/kg$.

$$\begin{aligned} &\iiint_{(x,y,z)\subset S_k} q_f(x,y,z)\cos(\gamma_q)dxdydz - \\ &\iiint_{(x,y,z)\subset S_k} g \cdot g_f(x,y,z)dxdydz - \\ &\iiint_{(x,y,z)\subset S_k} p_f(x,y,z)\cos(\gamma_p)q^{(k)}(x,y,z)dxdydz \cdot \Delta z^{(k)} \\ &= 0 \end{aligned} \quad (5)$$

To simplify the expression of displacement the along z-axis, let

$$\begin{aligned} Q_{Fz} &= \iiint_{(x,y,z)\subset S_k} q_f(x,y,z)\cos(\gamma_q)dxdydz \\ G_{Fz} &= \iiint_{(x,y,z)\subset S_k} g \cdot g_f(x,y,z)dxdydz \\ P_{Fz} &= \iiint_{(x,y,z)\subset S_k} p_f(x,y,z)\cos(\gamma_p)q^{(k)}(x,y,z)dxdydz \end{aligned}$$

Rewriting Eq. (5) in a simpler form, the following can be obtained:

$$\Delta z^{(k)} = \frac{Q_{Fz} - G_{Fz}}{P_{Fz}} \tag{6}$$

The displacements along the x and y axes, $\Delta x^{(k)}$ and $\Delta y^{(k)}$, can be expressed as in Eq. (7) and the corresponding symbols can be defined using Eq. (8).

$$\begin{aligned} \Delta x^{(k)} &= -\frac{Q_{Fx}}{P_{Fx}} \\ \Delta y^{(k)} &= -\frac{Q_{Fy}}{P_{Fy}} \end{aligned} \tag{7}$$

$$\begin{aligned} Q_{Fx} &= \iiint_{(x,y,z)\subset S_k} q_f(x,y,z)\cos(\alpha_q)dxdydz \\ P_{Fx} &= \iiint_{(x,y,z)\subset S_k} p_f(x,y,z)\cos(\alpha_p)q^{(k)}(x,y,z)dxdydz \\ Q_{Fy} &= \iiint_{(x,y,z)\subset S_k} q_f(x,y,z)\cos(\beta_q)dxdydz \\ P_{Fy} &= \iiint_{(x,y,z)\subset S_k} p_f(x,y,z)\cos(\beta_p)q^{(k)}(x,y,z)dxdydz \end{aligned} \tag{8}$$

A Special Case

In most cases, the clothing does not contact the human body, as with the bottom of a skirt as shown in *Figure 2*. In this case, the displacements along the three axes can be expressed using Eq. (9).

$$\begin{aligned} \Delta x^{(k)} &= 0 \\ \Delta y^{(k)} &= 0 \\ \Delta y^{(k)} &= -\frac{G_{Fz}}{P_{Fz}} \end{aligned} \tag{9}$$

From *Figure 2* and Eq. (10), it is deduced that the force components of the human body on the clothing are zeroes along two directions, which makes $\Delta x^{(k)}$ and $\Delta y^{(k)}$ becoming equal to zero. The displacement that exists along z-axis is determined by the gravity and the boundary of this block.

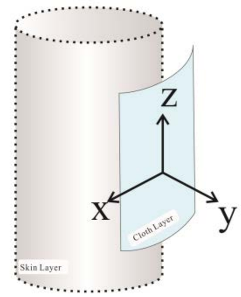

FIGURE 2. A special case force model in 3D space.

The actual clothing simulation in this case is shown in *Figure 3*. From the figure, it is observed that there are folds in the bottom part of the skirt, with the distance in this part being larger than a specific value. When this part is described as a block using Eq. (1), the effects of the fold in the bottom part of the skirt will be lost. Therefore, in this case, the lower and upper range in the general expression for the distance in Eq. (2) should be set in advance more accurately so that the effects of the fold in the clothing will be accurate and abundant as shown in *Figure 3*.

FIGURE 3. Bottom of the skirt in 3D space.

EXPRIMENTAL RESULTS AND SIMULATION

To verify the performance of the proposed scheme, a skirt is chosen to demonstrate the effects of the algorithm.

Distance and Block Determination

To determine the different blocks, the lower and upper ranges are predefined in *Table II*, where the symbol '∞' represents infinity.

TABLE II. Range values for the general expression of the distance.

Index	Lower range value	Upper range value
1	0	0.05
2	0.05	0.075
3	0.075	0.1
4	0.1	0.15
5	0.15	0.2
6	0.2	0.25
7	0.25	0.35
8	0.35	0.45
9	0.45	0.5
10	0.5	0.75
11	0.75	1
12	1	1.25
13	1.25	1.5
14	1.5	1.75
15	1.75	2.5
16	2.5	3.5
17	3.5	5
18	5	7
19	7	9
20	9	∞

Using Eq. (1) and the lower and upper range values in *Table II*, the desired blocks of the clothing can be computed and illustrated, as shown in *Figure 4*. From *Figure 4*, it is obvious that the shapes of different blocks vary accordingly Compared to the conventional methods like triangulated surfaces in [2], the proposed scheme forms different and irregular shapes since the block is a continuous area expressed in Eq. (1) constrained by the lower and upper range values in *Table II*. The sizes and shapes can vary accordingly to the lower and upper range values preset in *Table II*.

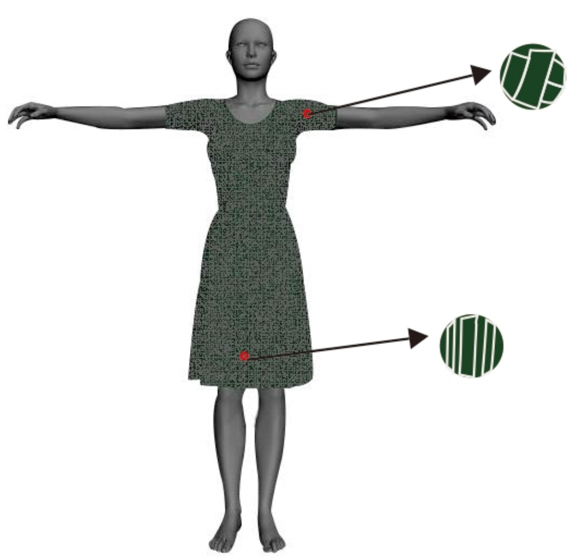

FIGURE 4. Block determination using the proposed scheme.

Force Model and Clothing Simulation

The force model in 3D space can be computed using Eq. (2) to Eq. (9). To illustrate the resultant forces of the clothing intuitively, a color demonstration legend is used, as shown in *Figure 5*. From the legend in *Figure 5*, it can be seen that the color lying in the bottom of the legend represents a small resultant force, while the color at the top of the legend denotes a large force. When all material in the skirt is assumed to be identical, the forces on the shoulder and the chest are large. The clothing located in these parts is tight to the human body; therefore, the major forces impacting the clothing are gravitational force on the clothing and the counterforce of the human body on the clothing. The bottom of the clothing does contact the human body, thus the major force on the clothing is gravity. From the above analysis, the resultant forces on the shoulder and chest should be larger than those located at the bottom of the skirt. From *Figure 5*, the results are in accordance with the analysis.

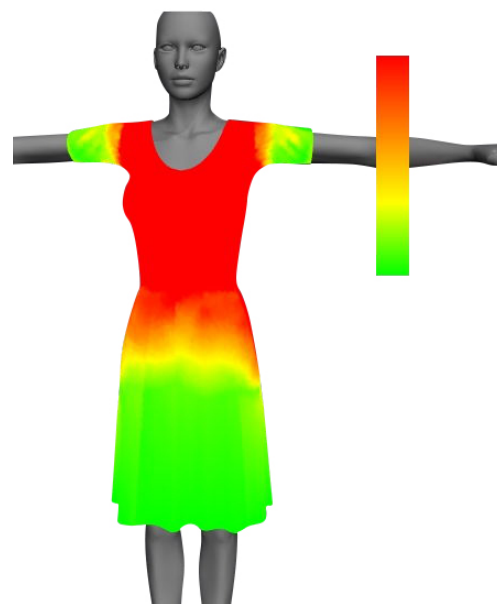

FIGURE 5. Force distribution of the clothing.

Subsequently, the displacement along the three axes from Eq. (6) and Eq. (9) can be observed at the bottom of the skirt using the simulation results depicted in *Figure 6.*

Simulation Speed Comparison

The time required for the simulation was calculated. The computer used to perform the simulation includes an Intel Core I5 650 central processing unit (CPU), 8GB memory and an ATI Radeon HD5450 graphics card. For clothing simulation speed analysis, the method in [22] is chosen as a comparison. For the desired skirt, the total time for simulation is 630 ms with the method in [22]. In a similar manner, the proposed scheme in this paper requires 503ms, a savings of about 20.2% in time.

Comparison of the experimental results and the simulation show that the proposed scheme can achieve acceptable simulation effects and effectively demonstrate the folds of clothing. In addition, the speed of the simulation is faster than that of the referring method. In summary, the proposed scheme demonstates improved accuracy and simulation time.

FIGURE 6. Clothing simulation in 3D space.

CONCLUSION

In this paper, an adaptive force model is proposed to obtain improved simulation accuracy and time. The distance can be determined using the lower and upper range in the proposed general expression. Using this distance range, a force model in 3D space is derived considering all the possible forces including gravity. This model effectively demonstrates the folds in clothing. Using this force model, the displacement along each axis in 3D space can be computed. In this manner, the deformation of the clothing on the human can be demonstrated. By adjusting the corresponding parameters, improved accuracy and shorter simulation times can be achieved. Experimental results show that the proposed scheme effectively simulates clothing in 3D space and simulation run time can be reduced as much as 38% compared to a reference method.

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