Evaluating simplified air force models for cloth simulation

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Abstract

Any cloth simulation system needs the aerodynamics model to describe the dynamic behavior of the cloth interacting with the air. Different air force models have different simplification treatment with different approximation degree. In this paper, we present a quantitative evaluation method for simplified air force models, and experimentally investigate 5 different air force models which are all commonly used in cloth simulations. The results show that the lift component, which was usually neglected in air force models, actually plays an important role in the simulation. Moreover, when the air field is simplified as the linear global wind field, the air force model containing the linear drag component and simple upward lift component matches the real cloth motion better than the complicated nonlinear ones.

1. Introduction

The air force is one of the most important factors contributing to the motion of cloth, especially when the cloth is swayed and interacts plenteously with the air. Appropriate air force model for cloth simulation should be chosen based on full knowledge of each model. However, the models used in previously developed cloth simulations have not been evaluated experimentally and quantitatively.

The air force is determined by two factors, the velocity of the cloth and the velocity of the air field around the cloth. The simulation of the air field, especially local air field around the cloth, is another complicated problem which was often neglected or simplified as the linear global wind field in cloth simulations for the sake of practicality.

L. Ling [1] developed a comprehensive aerodynamics model for cloth simulations which was hardly used in cloth simulations due to its high computational complexity. Keckeisen, M. et al. [2] decomposed the air force into two components: the drag force and the lift force. They also modeled two air field models to enhance the realism of simulation. The model in [1] was then simplified by [3] as a quadratic nonlinear drag force model, in which the air field and lift force were neglected. The most commonly used model is a linear drag force model as used in previous cloth work [4, 5]. H. Charfi. et al. [7] experimentally determined the parameter of this model. However, it is the only model evaluated in their experiments.

In this paper, we present a quantitative evaluation method for air force models. We choose 5 different air force models which have all been commonly used in cloth simulations. From the point of view of practicality, the air field around the cloth is simplified as the linear global wind field. The evaluation is made by comparison between the simulated cloth motion and the captured motion data of real cloth. First, we choose the linear drag force model as the benchmark. Then, the fractional approximation degrees of the other models are evaluated by the reduction of error between simulated data and the motion capture data.

Section 2 gives an overview of our method. Section 3 presents the simulation models. Section 4 describes the details about the algorithm of evaluation. Section 5 presents experiments and results.

2. Overview of our method

The air force acting on each triangle is hard to measure practically. To avoid this problem, we can compare the simulated cloth motion with motion capture data of real cloth, and then indirectly evaluate the air force model by the difference between them. For this purpose, parameters used in the internal force model and air force models need to be determined in advance. In this paper, we determine parameters by some genetic algorithm based optimization method.

Moreover, there is another problem. The difference between the simulated cloth and motion capture data is caused not only by the simplification of the air force model but also by the simplification of the internal force model and the air field. Hence, we choose one air
force model as the benchmark, and then evaluate other models by the reduction of difference between the simulated cloth motion and the motion capture data.

Furthermore, under the consideration of comparability, all simulated data are generated under the same internal force model and the same simplification of air field. The internal force model we used is a mass-spring system. In our experiments, air fields around cloth are all simplified as the linear global wind fields. Since the motion of real fabric was captured in an indoor environment, we could just make global wind field equal to zero.

Our evaluation method could be decomposed into two steps. In step 1, we choose a linear drag force model as the benchmark air force model. Then parameters in the cloth model will be determined by an optimization algorithm based on the motion capture data. The error of benchmark model is generated by the difference between motion capture data and simulated data using optimal parameters. Figure 1 shows the flow of step 1. In the second step, other air force models are evaluated by the reduction of difference between simulated cloth motion and the motion capture data. Figure 2 shows the flow of step 2. In this step, only parameters in the air force models will be determined by the optimization algorithm using motion capture data.

3. Cloth simulation model

Our framework for evaluating air force models is independent of cloth models. In this paper, we model the cloth based on the mass-spring system which was developed by [6] and had been improved subsequently by many researchers [4, 5]. The motion of cloth would be determined by the internal force and the external force.
The internal force could be calculated by following formula (1):

\[
f_{\text{spring}(p,q)} = \pm \left( k_s \left( \frac{\| x_p - x_q \|}{l_0} \right)^2 + k_d \left( \frac{\| x_p - x_q \|}{l_0} \right)^2 \right) \frac{x_p - x_q}{\| x_p - x_q \|}
\]

In which, \( l_0 \) is the default length of the spring, \( k_s \) is the stiff coefficient of the spring, while \( k_d \) is the spring damping coefficient, \( v_r \) and \( v_t \) represent the velocity and position of mass point \( p \), respectively. Since the internal force model describes the resistance of cloth to bending, stretching and shearing, there are 6 parameters needed to be determined for the internal force model when comparing simulated cloth data with the motion capture data.

The external force generally includes the gravity and the air force. The air force acting on each triangle could be decomposed into two components: the drag force and the lift force. In most of cloth simulations, as in [3,4,5], the part of lift force was neglected. In this paper, we would investigate 5 different air force models. Among them, there are 2 models without the lift component and 3 models with the lift component. On the other hand, these 5 models are partitioned to 3 linear models and 2 nonlinear models.

Model 1:

\[
F_{\text{air}} = F_{\text{drag}} = k_{\text{drag}} A \cdot (-v)
\]

Where \( k_{\text{drag}} \) is the drag coefficient. \( A \) is the area of the given triangle, and \( v \) is the relative velocity. If the air field is simplified as the linear global wind field, \( v = v_{\text{wind}} \). When there is no wind, \( v = v_{\text{fabric}} \).

In this paper, we choose model 1 as the benchmark air force model.

Model 2 [3]:

\[
F_{\text{air}} = F_{\text{drag}} = -A \left( k_n \left| v_n \right|^2 + \frac{v_n + k_f v_t}{1 + k_f \left| v_n \right|^2} \right)
\]

Where \( k_n, k_i, k_f \) are the drag coefficients. \( v_n \) is the normal component of \( v \), \( v_t \) is the tangential component of \( v \).

Model 3:

\[
F_{\text{air}} = F_{\text{drag}} + F_{\text{lift}}
F_{\text{drag}} = k_{\text{drag}} A \cdot (-v)
\]

\[
F_{\text{lift}} = k_{\text{lift}} A \cdot \hat{v}
\]

Where \( k_{\text{lift}} \) is the lift coefficient. \( \hat{v} \) is a unit upward vector.

Model 4:

\[
F_{\text{air}} = F_{\text{drag}} + F_{\text{lift}}
F_{\text{drag}} = k_{\text{drag}} A \left| v_n \right| (-\hat{n})
F_{\text{lift}} = k_{\text{lift}} A \cdot \hat{v}
\]

The unit normal of the given triangle is \( \hat{n} \). In the case of \( n \cdot v > 0 \), \( \hat{n} = n \), else \( \hat{n} = -\hat{n} \).

Model 5 [2]:

\[
F_{\text{air}} = F_{\text{drag}} + F_{\text{lift}}
F_{\text{drag}} = k_{\text{drag}} A \left| v_n \right| \cdot \left( \hat{n} \cdot v \right) (-\hat{v})
F_{\text{lift}} = k_{\text{lift}} A \cdot \hat{v} \cdot \cos \theta \cdot \hat{u}
\]

\[
\hat{u} = (\hat{n} \times \hat{v}) \times \hat{v}
\]

Where \( \theta \) is the angle between \( v \) and the triangle. \( \hat{v} \) is the unit vector of \( v \).

4. Model evaluation

4.1 Motion capture data
We have captured cloth motion by the Motion Capture Device in an indoor environment (Figure 3). Two pieces of square cloth with different materials have been chosen as examples. Each has an area of 450mm × 450mm. Marks made by sticky reflective paper were stuck on samples. The marks need to be thin and small (as shown in the figure 4), so that it is far lighter than the cloth itself.

In motion design, on one hand, the data captured should be able to present motion features of the particular fabric as much as possible; on the other hand, effective data must be sufficient so that the global convergence could be ensured in optimization. We took the left upper vertex and right upper vertex of the cloth as control points, and manually drove cloth swaying back and forth. Each group of motion was started from the static state. For each sample, effective data with about 800 frames were captured, which is far more than the result in paper [8].

4.2. Parameters optimization

The essence in optimization is to find a set of parameters, which minimize the error between simulated motion data and the motion capture ones (MOCAP data). The workflow of our optimization method is shown in figure 5. We chose the genetic algorithm for global optimization, in which the smaller error between simulated data and MOCAP data, the higher individual’s fitness, and the stronger genetic dominance; Otherwise, the lower fitness.

4.3. Data comparison

Under the consideration of comparability between simulated data and motion capture ones, there are some operations must be followed. First, marks on samples should be regularly permuted in the equal interval as shown in figure 4. In the motion capture process, each group should be started from the static state and the artificial driven force must be exerted only on the two control points.

Second, before simulation, the mass-spring model needs to be initialized with the static state of the sample. The amount and the positions of masses points must be in strictly (one-to-one) accord with the marks on the sample. Default lengths of springs should also be calculated under the static state. In the simulating process, such two mass points corresponding to the control points would be driven by motion capture data directly. The rest mass points could be calculated by simulation.

After operations mentioned above, the calculated positions of mass points would be comparable with the captured positions of the corresponding marks. Therefore, we could get the difference between simulated data and motion capture data by the formula as follows:

\[
e = \frac{1}{nm} \sum_{i=1}^{n} \sum_{p=1}^{m} |x_{ip} - c_{ip}|
\]

where \( n \) is the length of motion data in MOCAP data; \( m \) is the amount of marks except for control points. \( x_{ip} \) is the position of the mass except for control points in the \( i \)th frame, and \( c_{ip} \) is the coordinate position of the corresponding mark.

5. Experiments and results

In our experiments, we selected two different fabrics, silk and thin wool, and manually drove them interact plenteously with the air. For each fabric,
motion data were captured by device and about 800 frames were processed as samples. In the first step, we chose the model 1, the linear drag force model, as the benchmark air force model. Cloth simulation parameters, including parameters in the internal force model and model 1, were optimized. Then benchmark error was calculated by the optimal parameters.

In the second step, parameters in other air force models were optimized. Then these models were evaluated by the reduction of difference between simulated cloth motion and the motion capture data, which could be calculated as follows:

$$d = \frac{e_{\text{benchmark}} - e}{e_{\text{benchmark}}}$$ (11)

Where $e_{\text{benchmark}}$ is the error of benchmark air force model. $e$ is the error of other air force model.

<table>
<thead>
<tr>
<th>Model</th>
<th>Silk</th>
<th>Thin wool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 2</td>
<td>-28.37%</td>
<td>-34.14%</td>
</tr>
<tr>
<td>Model 3</td>
<td>45.71%</td>
<td>43.12%</td>
</tr>
<tr>
<td>Model 4</td>
<td>41.13%</td>
<td>40.37%</td>
</tr>
<tr>
<td>Model 5</td>
<td>21.15%</td>
<td>24.34%</td>
</tr>
</tbody>
</table>

Table 1. Error reduction of different air force models

Obviously as showed in table 1, air force models containing the lift component are all have positive error reduction. That means air force models with the lift component are more realistic and match motion capture data better than models without the lift component. Comparing model 3 with the benchmark model, we could find that by adding simple upward lift force as calculated by formula (5), error could be decreased more than 40%.

Comparing model 2 with the benchmark model, and comparing model 3/4 with model 5, we could find that linear force models are more effective than the nonlinear ones in both drag component and lift component. It sounds strangeness. However, it is reasonable. Since the air field is simplified as the linear global wind field, under such condition, the air force square of $v$ will increase error. The results show that air force models containing the linear drag component and simple upward lift component, like model 3 and model 4, are the better choices for cloth simulation than nonlinear models, under the condition of that the air fields is simplified as the linear global wind field.

Figure 6 shows the 3D simulation results compared with the motion capture data. The red points are marks in the motion capture data. Each row shows the results at 3 frames chosen from a long sequence. In each row, the air force models, from left to right, are model 1 to model 5 one by one. Obviously, model 3 and model 4 match the motion capture data better. More 3D simulation results could be found in the attached video.

Additionally, in order to verify the validity of the parameters optimization method, we use another group of motion data for verification and error analysis. We find that the relative position deviation per 5 seconds between simulation result (using air force model 3) and real data of each material of cloth is less than 6%.

6. Conclusion

The air force plays an important role in cloth simulations. In this paper, we present a method to evaluate air force models experimentally and quantitatively. Five commonly used air force models have been investigated using our method.

We select model 1 as the benchmark and evaluate other models by the reduction of difference between simulated data and motion capture ones. All simulated data are generated with the same internal force model. Like most of the cloth simulation works, the air field around the cloth is simplified as the linear global wind field for the sake of practicality.

From our experiments, we have found two important conclusions.

The first is that: the lift component, which was usually neglected in air force models, actually plays an important role in simulation. Adding simple upward lift force as calculated by formula (5), simulation error could be decreased more than 40%.

The second is that: when the air field is simplified as the linear global wind field, the air force model containing the linear drag component and simple upward lift component matches the real cloth motion better than the complicated nonlinear ones.

7. Acknowledgements

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Figure 6. Snapshots of 3D simulation results compared with motion capture data. Snapshots from left to right are simulation results by model 1 to model 5.

8. References


