Realistic Skeleton Driven Skin Deformation

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Abstract. Skeleton driven animation is a popular method for the animation of deformable human and creature characters. The main advantage is its computational performance. However it suffers from a number of problems, such as collapsing elbow and candy wrapper joint. In this paper, we present a new method which is able to solve these defects; reduce the animator's manual work still allowing his/her full control over the process; and realistically simulate the fat bulge effect around a joint.

1 Introduction

Skin deformation is one of the most important issues in realistic character animation and has received a great deal of attention from the animation research community over the last two decades. There are currently two prevalent approaches, one is based on the anatomy of the human/creature characters and the other deforms the character skin directly.

The anatomy based technique tries to mimic the muscle structure of a human or creature. Normally three layers are used, the skeleton, musculature and possibly fat, and the skin layer [1]. This approach usually works by layering individual CG (computer graphics) muscles on the skeleton. These muscles deform (stretch or bulge) following the motion of the skeleton. The final skin takes the overall shape of the muscle and fat layer of the animated character body. Because the skin shape is derived from the underlying structures, this approach affords good graphical realism. The disadvantage, however, is that it is tedious and unintuitive to use. Not many people in the animation industry employ this approach due to these drawbacks.

The second approach, often known as the smooth skinning technique, makes no direct use of the anatomical elements. The skin shape is controlled by the transformations associated with the joints of the skeleton. This technique is simple to use and very fast to compute. Due to these advantages, it is the most popular in animation production and has been incorporated into many animation packages. As it uses a very simple shape blending technique to deal with an inherently very complex matter, it is understandable that this technique is not expected to cover all skin deformation problems. In practice, it suffers from a number of defects, some of which are very difficult to rectify. Typical problems

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include collapsing elbow, candy-wrapper joint when the arm turns 180 degrees, and intersection between two adjacent bones (links) around a joint. These problems are especially obvious around the shoulder and elbow areas. Manual efforts are often the only option, which can be tedious and undesirable. To understand the cause of these problems, the reader is referred to [2].

1.1 Previous work

Skin deformation has been an interesting research topic for a long time. Two dominating techniques exist as stated above, one based on anatomy and the other is not.

The anatomy-based technique is able to achieve very good graphical realism on the skin surface. Physical properties [3] can be associated with the individual anatomical elements, such as muscles and other internal elements. When driven by the skeleton, these anatomical elements move and deform accordingly resulting in realistic deformation of the skin surface. There is a large amount of development in this area including Wilhelms and Gelder [4], Scheepers et al. [1], and Aubel and Thalmann [5]. Despite its strength, this approach has not proven popular in animation production, due to the above mentioned disadvantages.

The traditional skinning model, which involves no knowledge of anatomy, goes by various names. Lewis called it Skeleton Subspace Deformation (SSD) [2] and the software package Maya calls it Smooth Skinning. In this paper we will also adopt this name. An introduction of this technique can be found in Lewis et al [2].

Catmull [6] introduced one of the first skeleton-driven techniques to animate an articulated figure. An early 3D skeleton-driven technique that involves deformable skinning was presented by Magnenat-Thalmann et al. [7]. This technique deforms character meshes using the motion of particular joints.

Later improvements have been aiming to both improve realism and reduce tedious manual intervention. One effective idea is to use a large number of examples, which may be obtained either by manual modelling or by range-scanning. Wang and Phillips [8] proposed a least squares multi-weight technique to compute the weights of the elements of the transformation matrices based on examples that are usually hand-modelled. The technique by Allen et al [9] is also based on many examples produced by laser-scanning. The idea is to interpolate the scanned key shapes to derive a fuller set of shapes. Both techniques are able to produce very realistic results, but all rely on the availability of a large number of pre-obtained models.

1.2 Overview

Our aim of this paper is to retain the strength of the popular smooth skinning technique and keep the current production pattern unchanged, in the meanwhile to allow the graphical realism to be significantly improved. Thus the animator can continue with their pattern of practice which they have been used to for a long time. In particular, we make two important contributions:

- Non-linear skin deformation. Current techniques either require heavy manual input or blend shapes in a linear manner. We have found linear shape blending to be a cause for many unpleasant defects. In this paper, we present a non-linear technique to solve this problem.
- Fat bulge effect. When an arm bends, the flesh is pushed out sidewise due to the property of volume preservation. This phenomenon, despite its subtlety, has a profound effect on realism. In this paper, we present an efficient algorithm to model it effectively.

The remainder of the paper is structured as follows. In Section 2 we present our nonlinear smooth skinning method. We will first introduce briefly the traditional technique. Then we discuss how it is improved to produce visually pleasant results. Section 3 discusses the modelling of the subtle fat effect at a bent joint. Section 4 concludes this paper.

2 Nonlinear smooth skinning

As will be seen below, the defects of the smooth skinning technique is to some extend caused by the linear interpolation mechanism involved. In this Section, we present a new technique to remedy this problem.

2.1 Smooth Skinning

Current linear blend skinning algorithms work by first placing a skeleton inside a character model, usually in a neutral pose. Each vertex is then assigned a set of influencing joints together with a weight factor corresponding to each influencing joint. Deforming the character into a different pose involves transforming each vertex from the initial pose by all the influencing joints. The transformed positions are finally blended together to give the final position of all the vertices. At a skeletal configuration c, a deformed vertex V_c, can be computed by [10]:

$$V_c = \sum_{i=1}^{n} w_i M_{i,c} M_{i,d}^{-1} V_d \tag{1}$$

where w_i are the weights, V_d is the location of a vertex at its initial pose, $M_{i,c}$ denotes the transformation matrix associated with the ith joint in configuration c and $M_{i,d}^{-1}$ the inverse of the transformation matrix associated with the ith influencing joint.

This skinning algorithm is very fast and widely adopted by animation software packages. However as discussed earlier, it fails for complex deformations and suffers from a number defects such as collapsing elbow and shrinkage around a joint.

2.2 Nonlinear skin deformation

All these problems are rooted from how the vertex weight is computed. Most animation software leaves this work to the animator who paints the weight by hand. Understandably, building a complete sequence of poses entirely by hand is very time-consuming. Attempts were made to relieve the animator from the drudgery, such as [8] and [10] by trying to reverse-engineer the weights from a well defined pose space. However, problems remain if such a pose space, usually constructed from a large number of existing example models, is not available.

In this paper, we present a method for direct assignment of weights to the vertices according to its position around the joint. The method is introduced in three steps as follows.

Weight computation The weight coefficient modulates the influence of a joint to the point concerned. To develop an effective weight computation model, we first define the properties that an ideal model should satisfy, which are given as follows:

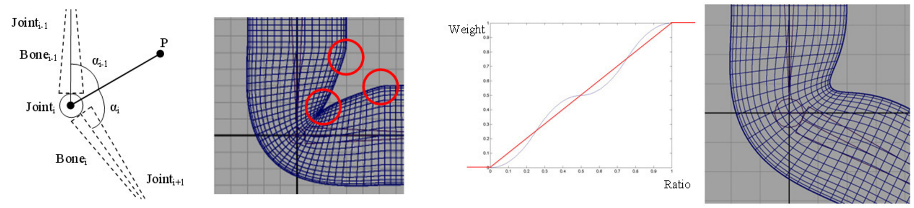
- Smoothness within influenced region. Eq. (1) suggests that smooth skinning transforms a point to a new position defined by blending all relevant transformations together. Linear blending often suffers from lack of smoothness. To ensure satisfying smoothness, a higher degree of continuity is necessary, at least with a tangent continuity. This suggests the necessity of a nonlinear weight computation model.
- Smoothness at the boundary of an influenced region. To avoid sudden changes at the boundaries of an influenced region, weights should change gradually, i.e. avoiding large weight discrepancy at the boundaries.
- (c) Symmetry. To avoid a biased shape, the weights should be distributed approximately symmetrically.

To facilitate discussion, we also need to define some quantities. The closeness of the point concerned, P, to an individual bone (link) j is measured by the *influence angle* α_j (Figure 1a). If $\alpha_j < \alpha$, where α is called the *limit angle*, then point P is influenced only by the transformation associated with joint j, otherwise, P is influenced by the neighbouring joints. The limit angle is specified by the user to indicate how much influence the skin should be affected by the neighbouring joints. Another useful quantity is called the *influence ratio* r, which is defined below:

$$r = \frac{\alpha_{i-1} - \alpha}{\alpha_{i-1} + \alpha_i - 2\alpha} \tag{2}$$

where α_{i-1} or α_i are influence angles (Figure 1a). The default weight value of P influenced by joint i is thus given by:

$$W_i = r \tag{3}$$



a b c d

Fig. 1. Weight computation: (a) Parameters (b)Linear smooth skinning (c)Weight distribution (d) Smooth skinning

This however, is not satisfactory. Figure 1b shows the resulting deformation on a Nurbs surface. Discontinuity is evident as marked by the red circles. This is because the linear relationship between the weights and the influence ratio r (the red line shown in Figure 1c). Improvement can be made by defining a higher order function of r, which satisfies the three conditions stipulated above. For this purpose, we propose the following polynomial form:

$$W(r) = \sum_{i=0}^{d} a_i r^i \tag{4}$$

where a_i are the unknowns, which should be determined by satisfying conditions (b) and (c), as (a) will be automatically satisfied by Eq. (4).

It is easy to see that conditions (b) and (c) are equivalent to the following constraints:

$$\begin{array}{l} W(0.0) = 0.0 \;\; W(0.5) = 0.5 \;\; W(1.0) = 1.0 \\ W'(0.0) = 0.0 \; W'(0.5) = 1.1 \; W'(1.0) = 0.0 \end{array} \tag{5}$$

$W(0.5) = 0.5$ makes the distribution roughly symmetric and $W'(0.5) = 1.1$ is chosen according to our experiment results. Using these 6 constraints (5), one is able to determine the unknowns α_i from (4) by solving a set of linear equations. Thus we obtain the following weight distribution equation:

$$W(r) = -6.4r^5 + 16r^4 - 14.8r^3 + 6.2r^2 \tag{6}$$

Figure 1d shows the improved result using Eq. (6).

Compensation for a collapsing joint Collapsing joint as a result of big bent angles, is another typical problem. The artefacts occur because the vertices are transformed only in a linear manner, i.e. no consideration is given to its angular contribution.

To rectify this problem, we first compensate the shrinkage by pulling the skin surface away from the joint, and then blend the influences from relevant joints angularly. Assume J is the joint centre (Figure 2), P_1 and P_2 are the transformed

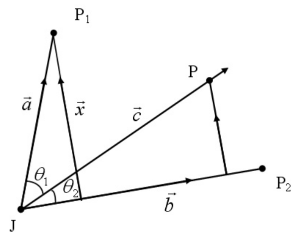


Fig. 2. Interpolation of vertex near joint

positions obtained using the transformation matrices of the two related joints respectively. The new position of the point P is given by:

$$P = \frac{\vec{b}}{\left|\vec{b}\right|}\left|\vec{c}\right|\cos\theta_2 + \frac{\vec{x}}{\left|\vec{x}\right|}\left|\vec{c}\right|\sin\theta_2 \tag{7}$$

where

$$\begin{aligned}
&\vec{a} = \overrightarrow{OP_1} - \overrightarrow{OJ} \ \vec{b} = \overrightarrow{OP_2} - \overrightarrow{OJ} \\
&\theta = \arccos\left(\frac{\vec{a} \bullet \vec{b}}{|\vec{a}||\vec{b}|}\right) \\
&\theta_2 = \theta * (1 - W_i) \ \theta_1 = \theta - \theta_2 \\
&\vec{x} = \vec{a} - |\vec{a}|\cos(\theta_1 + \theta_2)\frac{\vec{b}}{|\vec{b}|} \\
&l_2 = |(\overrightarrow{OP_2} * W_i + \overrightarrow{OP_1} * (1 - W_i)) - \overrightarrow{OJ}| \\
&W_i' = 1 - 4 * (W_i - 0.5)^2 \\
&l_1 = |\vec{b}| * W_i + |\vec{a}| * (1 - W_i) \\
&|\vec{c}| = l_1 * W_i' + l_2 * (1 - W_i')
\end{aligned} \tag{8}$$

where W_i stands for the weight of joint i, O is the origin of the world coordinate system. Figure 3 compares the result for this method. Compensation is effective not only at the inner part but also the outer part of the joint, which is a desirable feature.

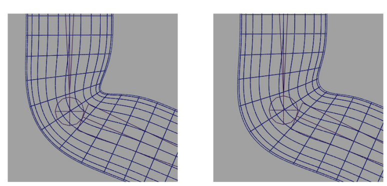


Fig. 3. The compensation result (left: uncompensated, right: compensated)

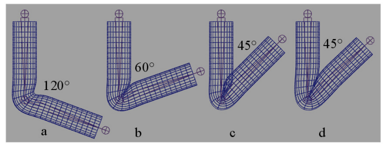


Fig. 4. constant angle for the joint affect scope limit

Limit angle The limit angle is another powerful tool, which specifies the influenced scope of a joint. So far this quantity is set as a constant angle. However, by changing this angle in response to the bent angle of a joint, more desirable results can be achieved. In Figure 3, for example, this angle is set to be 30 degrees. This works fine until the bent angle reaches 60 degrees. If the joint bends further, interpenetration starts to show up. From our experience, the joint will deform reasonably if the angle between the two adjacent bones is not smaller than a double of the limit angle. This suggests that for better deformation result, the limit angle should change dynamically to suit individual cases. In Figure 4 the limit angle is set to be 30 degrees, which is well-behaved for the first two cases where the bent angles are 120 and 60 degrees, respectively. Intersection arises for the third one when the bent angle reduces to 45 degrees. However, if the limit angle is reduced, the problem goes away (Figure 4d).

3 Fat bulge effect around bent joint

So far as the visual realism of a human character is concerned, the fat effect comes into play with two contributions. It smooth out the shape obtained from the muscle formation under the skin. The second gives the bulge effect around a joint. When a joint bends, the flesh under the skin is pushed out due to the property of volume preservation.

While the first is relatively easy to do, the second problem proves much harder, as the shape changes dynamically as the joint bends. Current techniques unfortunately struggle to maintain a constant volume level, which result in unrealistic skin shapes. Figure 5 shows our analysis results. The bottom curve records the volume loss from Eq. (3) and the top one from Eq. (7), which compensates the shrinkage around a joint. Although the compensation method Eq. (7) improves the situation, further improvement remains necessary.

Accurate bulge effect can be computed with physical simulation, which nevertheless is by no means an easy task and usually is computationally expensive. Here we present a geometrical method to achieve satisfactory visual look in real-time. As fat is largely incompressible, when a joint bends, flesh between the adjacent bones will be squeezed, producing bulges immediately near the joint and at the sides. The main idea of our method is to formulate a surface function able to both represent the bulge distribution and the deformation linked with the joint angle parameter.

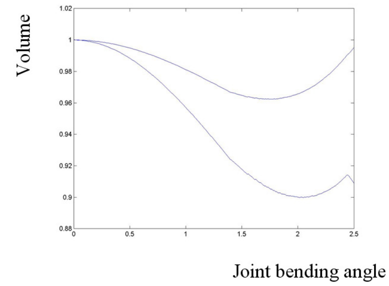


Fig. 5. Volume loss by current methods

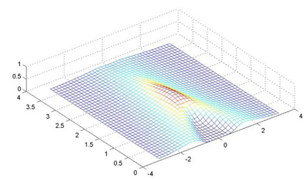


Fig. 6. Fat bulge distribution and ridge curve

Within a cylindrical co-ordinate system, the bulge distribution can be described as a surface, and the ridge forms a curve on this surface as seen in Figure 6.

The ridge curve can be defined as,

$$y = \frac{2\pi - 4\alpha_0}{\pi^2} x^2 + \alpha_0 \tag{9}$$

where α_0 is the limit angle of the joint. The closer to the ridge curve, the bigger bulge occurs and the height roughly takes the normal distribution centred at the ridge curve. This suggests that for each skin vertex $P(x_0, y_0)$, we have the following bulge function,

$$P(R) = \begin{cases} 16A(R-1)^4 - 8A(R-1)^2 + 0.5 & 0.5 < R < 1.5 \\ 0 & R \leq 0.5 \\ 0 & R \geq 1.5 \end{cases} \tag{10}$$

where A is a parameter associated with the volume loss from Fig.5 and

$$R = \frac{y_0}{\frac{2\pi - 4\alpha_0}{\pi^2} x_0^2 + \alpha_0} \tag{11}$$

Figure 7 shows the fat bulge distribution surface and Figure 8 shows the deformation of a cylinder-shaped "arm", which was computed by the nonlinear smooth blending and fat bulge compensation methods presented in this paper.

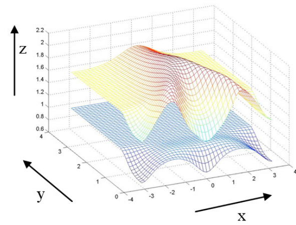


Fig. 7. Fat bulge effect superimposed on the skin shape produced by the compensation method presented above. In this cylindrical co-ordinate system, x stands for the azimuth coordinate, y for the distance from the joint along the limb, z for the radial coordinate. For each vertex on the skin surface, the deformation only affects its z value. The bottom mesh shows the skin deformation around a joint using our compensation method. The top mesh, the final result including fat bulge, adds contribution from the fat layer to each vertex's z coordinate according to the bulge distribution function defined in Eq. (9).

4 Conclusion and future work

We have presented a new smooth skinning method for character skin deformation. By setting up a set of criteria that a skinning method should satisfy, we have derived a nonlinear weight distribution function. Unlike other existing weight computation methods, our method does not rely on pre-made examples. Current techniques suffer from a number of defects, such as the clasping elbow problem. In this paper, we have studied the cause of such problems and presented an effective remedy. We also find that dynamically adjusting the limit angle is of a practical value in producing desirable deformation results. Using this technique, the animator is able to produce realistic skin deformation easily and still able to exercise his/her control.

Fat bulge effect adds further realism to a deformable animated character. In this paper we have presented a fast method to model this phenomenon. Although no accurate physics was involved, this method achieves convincing visual results.

We have implemented our method into a plug-in in the Maya Environment alongside the traditional smooth skinning technique. We also present the animator a user-interface to control the important parameters, such as the fat region and bulge dimension. Our method works very well on the character's limbs. On the body, however, because it involves more than two bones, the compensation method is less effective. We would like to improve this matter in the future.

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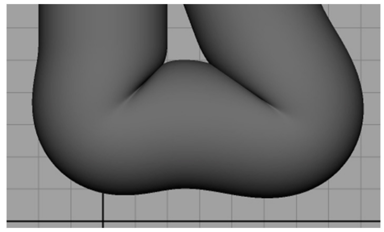

Fig. 8. Fat bulge distribution and ridge curve

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