Physically-based Wrinkle Simulation & Skin Rendering

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Abstract

Wrinkle simulation with skin modeling and deformation are extremely important in enhancing the realism of human figure models. In this paper we present a model which simulates the skin deformation based on a biomechanic model and generates dynamic wrinkles rendered with texture image. The biomechanical model considers the skin as a membrane undergoing large deformations and puts the local coordinate system of each triangle element to its principal strain directions. Synthetic micro and macro structure patterns combined with real photos are employed as texture images to mimic the skin surface details. Furthermore, the potential wrinkle lines are defined , the dynamics of expressive wrinkles and aging wrinkles --their depth and fold-- is modeled based on the principal strain of the deformed skin surface and duration of deformation. Multi-layered color and bump texture mapping is used for skin rendering.

Keywords: Skin, Wrinkle, Aging, Texture, Deformation.

1. Introduction

The modeling and rendering of skin is very important for human figure modeling because it greatly enhances the realism of the character animation. The skin is a continuous, protective sheet that envelops the entire body and is attached to the deeper structures by way of connecting tissues. This is the outer most visible layer of the body. At a number of places, skin adheres closely to its underlying tissue, elsewhere it glides rather freely, and at some places it becomes recessed and puckered into wrinkles [Fung, 93].

The outer skin surface consists of a geometrical structure which manifests the form of visible skin. This may look different for different parts of the body depending on its characteristics and how it is attached to the body. However, skin when observed from a close-up depicts a micro structure which is common for most parts on the body. This *micro structure* has a rather well defined geometrical shape and form resembling a pattern with a layered net-like structure. This structure consists of polygonal forms, most often triangles [Marks 83]. The edges of the triangular forms define the location of furrows or micro lines, and the curved surface surrounded by furrows define the ridges. On the other hand, the visible lines, patterns, creases and folds constitute a distinct structure which may be specific to one part; this structure we refer to as a *macro structure*. The macro structure defines the characteristic features of skin associated to a region of the body such as visible deep flexure lines and potential wrinkle lines. The macro lines form deeper and wider furrows and creases as compared to the micro lines. The micro and macro structures over skin constitute major elements affecting its visual appearance.

Skin mainly consists of collagen and elastin fibers whose combined effects decide skin's mechanical properties. Skin is usually considered as an incompressible and anisotropic material that has a visco-elastic behavior and becomes plastic with time. Two types of wrinkles appear with skin deformation: expressive wrinkles and wrinkles due to age (particularly for the face). Expressive wrinkles appear on the face during expressions at all ages and may become permanently visible over time. Skin changes with age. More lines and wrinkles emerge and with time the general appearance and texture of the skin become pronounced and rough. In addition to their visual effects, wrinkles indicate the age of a person, and expressive wrinkles act as an important factor for understanding and interpreting facial expressions.

Varied models are used to simulate skin deformation for different purposes. There are geometric models, physically-based models and biomechanical models using either particle system or continuous system. Many geometrical models have been developed. For examples, Parke [74, 82] used parametric models; Waters [87] and Magnenat-Thalmann [88] proposed models based on muscle actions of the face. There are also different kinds of physically-based models. Platt [81] proposed a tension-net model for facial animation. Terzopoulos [90] and Lee[95] used a three layered deformable lattice structure for facial tissues. Finite Element Method is also employed for more accurate calculation, especially for medical applications such as plastic surgery [Larrabee 86, Pieper 92, Koch 96].

Many research efforts have been undertaken for generating skin textures for animal as well as human skin. Bump and color mapping techniques as well as texture synthesis language are used to simulate reptile skin pattern [Miller 88, Kaufman 88]. Nahas et al. [90] proposed a method for obtaining the skin texture by recording the data of a human face. Ishii et al. [93] also proposed a geometric model for skin micro structures which applies a curved surface on a based polygon for expressing folds and ridges. There also exist a few commercial softwares (such as Alias-Wavefront) which include texture mapping features, where a photograph can be mapped on a 3D object. Most of these softwares do not impose position correspondence for the features in the model and the image [Kalra 93]. Furthermore, there does not exist yet a method where the texture image is modified as a function of skin deformation.

There have been a few efforts for the dynamic wrinkles with skin deformation. Viaud et al. [92] have presented a geometric hybrid model for the formation of expressive wrinkles, where bulges are modeled as spline segments. Terzopoulos and Waters's model [90] produces some of the expressive wrinkles during the skin deformation. A simplified facial model with a two dimensional lattice skin surface is proposed to simulate expressive wrinkles in facial animation and the aging process [Wu 1994].

However, the present models do not provide a unified framework to generate different kind of wrinkles with animation. Texture mapping offers a good simulation of static wrinkles, but it is difficult to mimic the wrinkle dynamics during animation by a purely geometric model with texture mapping. A physically based approach can offer a better simulation of wrinkle formation, but if it requires geometrical modeling of all the wrinkles it may be expensive. Therefore, in our model, the deformation of skin is motivated by a simulated muscle layer and decided by a biomechanical model while the wrinkle formation and rendering nuance are reflected by several layers of color, bump or displacement texture mapping. The texture images consist of synthetic patterns as well as real photos. The influence of the skin deformation to wrinkle formation is affected by controlling their bulge depth according to the principal strain at the skin surface points.

The paper is organized as follows. In Section 2, we give an overview of the skin deformation and wrinkle simulation mechanism. Section 3 describes the muscle design process in which muscles are simplified as B-spline patches. In Section 4, a biomechanical skin model is presented, which employs a biaxial plane-stress elastic constitutive relationship to the membrane undergoing large deformations. In addition, a linear plastic process is applied to form permanent wrinkles. Section 5 presents wrinkle simulation and its rendering with texture images. Finally, we give some concluding remarks in Section 6.

2. Overview

The skin is attached to the underneath muscle and subcutaneous layers by connective tissues. A three layered structure: an outer layer of skin with two inner layers of muscles and connective tissues, is used for skin deformation (See Figure 1). The skin surface is represented as a triangle mesh, having material properties associated with triangles but kinematical features with vertices. During animation, muscle contractions apply tension to the skin surface through insert points while the connective tissues constrain the skin deformation through connective points [Wu 94].

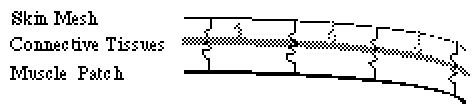
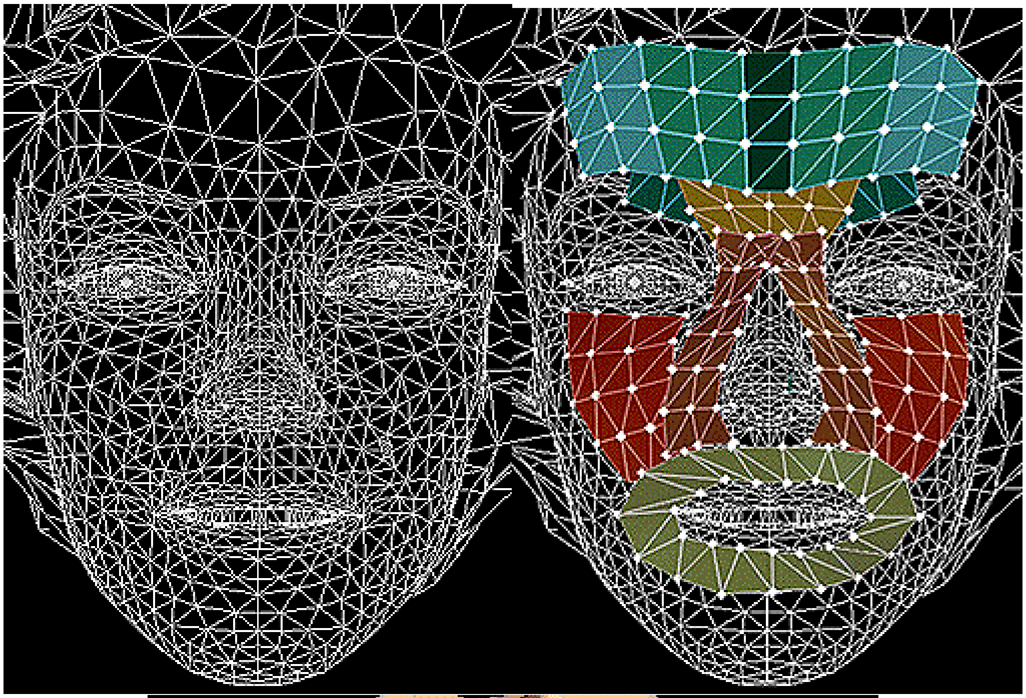
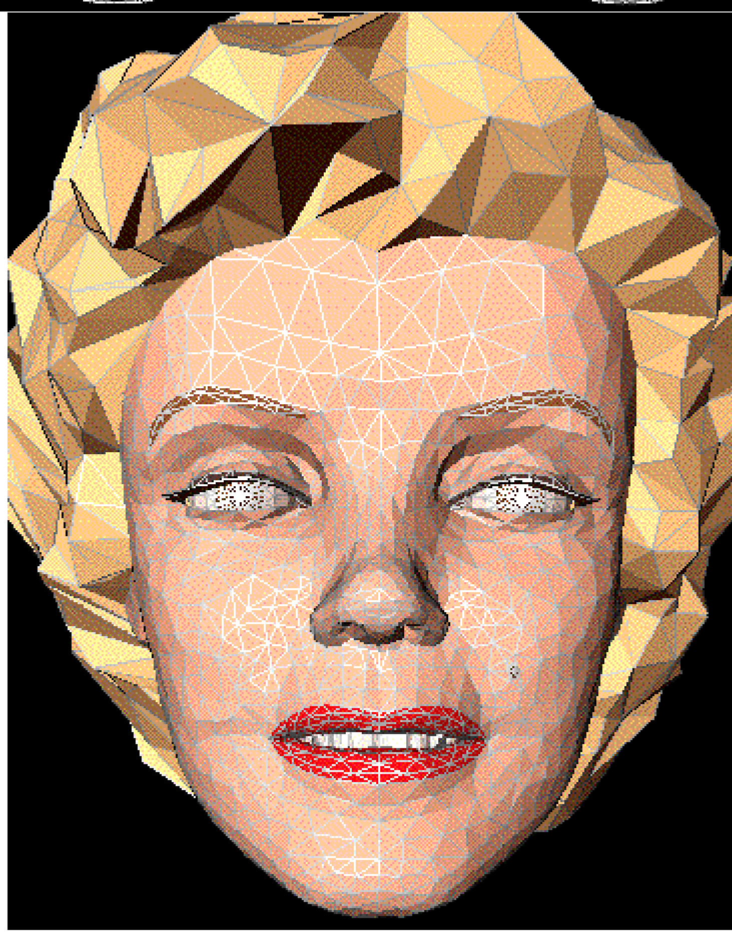
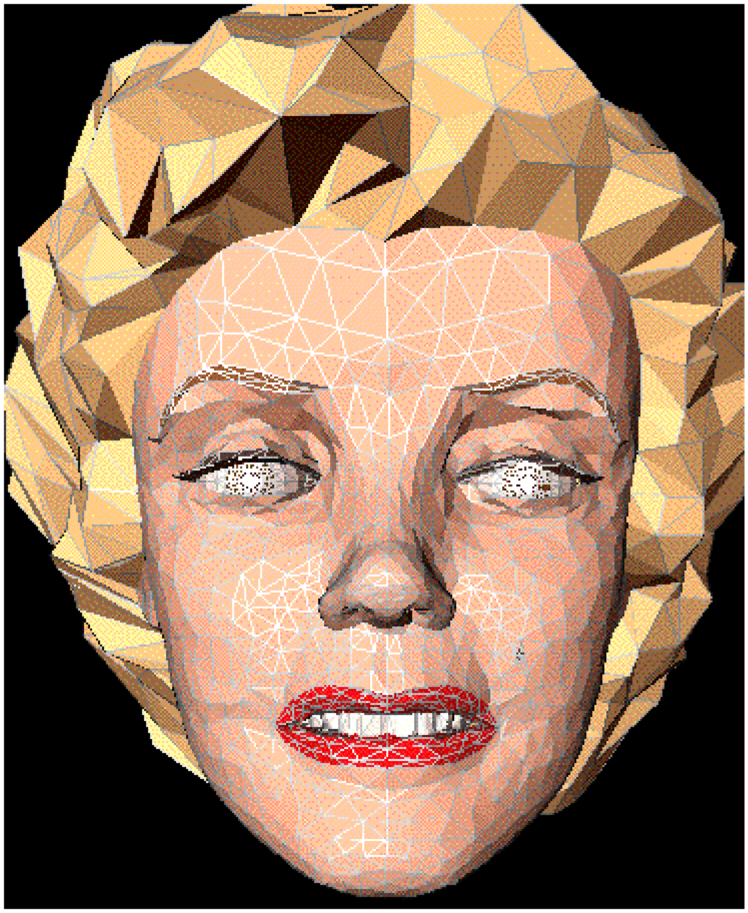


Figure 1: Layered Structure for Skin Deformation

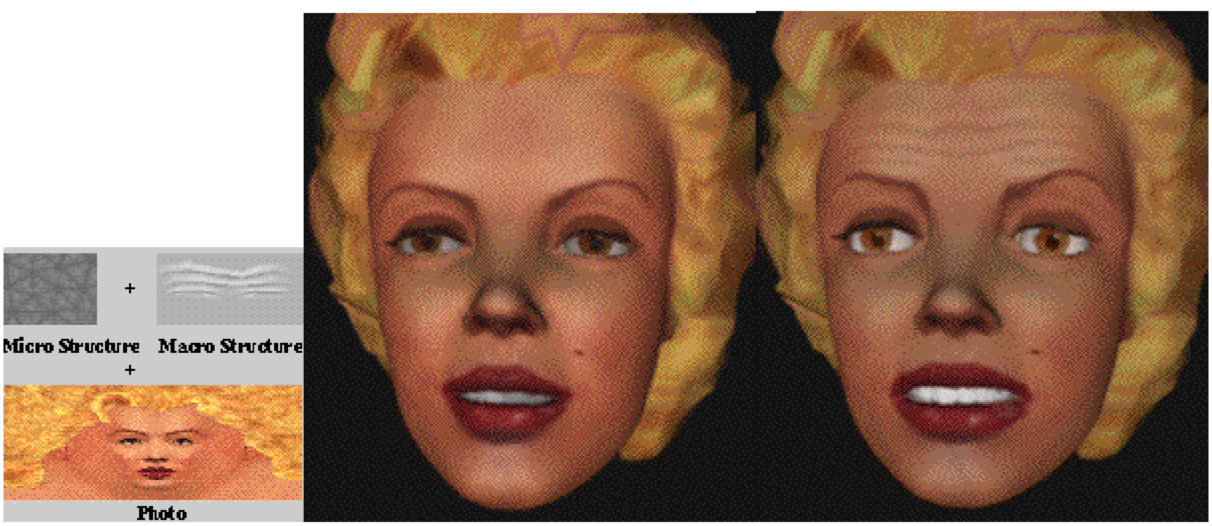
Fig 2 shows the overview of our wrinkle simulation prototype. In our facial model the skin's geometrical structure is defined as a triangle mesh. Facial muscles are designed as B-spline patches according to the nature and direction of muscle fibers. The skin surface is deformed using a biomechanical model following muscle contractions. Patterns for static wrinkles are represented in texture images. The dynamics of wrinkle simulation is computed using the strain measures of skin deformation of the 3D facial model. The wrinkle formation information modifies the corresponding synthetic wrinkle pattern texture image. Final rendering may combine texture mapping of real photos and synthetic skin texture using a layered rendering process of RenderMan[Upstill 89].







(a) Skin Surface (b) Muscle Design (c) Skin Deformation



(d) Wrinkle Formation and Rendering

Figure 2: The Overview of Skin Deformation and Wrinkle Simulation Process

3. Muscle Design

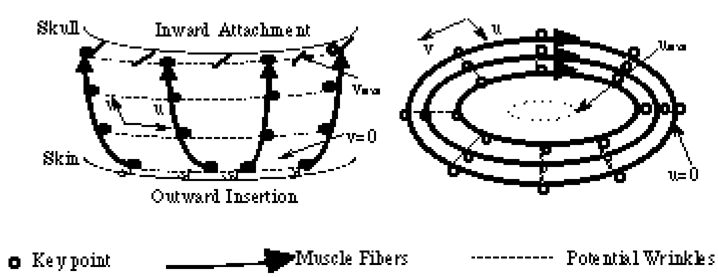
Muscles are principle motivators of skin deformation so that when a muscle contracts, it attempts to draw its attachment together. Though muscles have a large variety of sizes, shapes and complexity, they are essentially bundles of fibers lying and operating along some direction in unison. In this section, we will discuss simplified facial muscle design which produces reasonable results.

3.1. Muscle Patches

Facial muscles mostly consists of cluster of fibers with a rather flat structure so that surface models can be used to simulate muscles instead of volume models. A muscle has a biaxial structure and behavior because of its fiber configuration. Due to the biaxial nature along its two parameters, B-spline patch is chosen for muscle representation in our model.

The facial muscles are classified into two main types: linear muscles and sphincter muscles. A linear muscle contracts toward the static attachment on the bone such as the frontalis major muscle which raises the eyebrows. A sphincter muscle contracts around an imaginary central point such as the obicularis oris muscle which draws the mouth together [Waters, 87]. Open B-spline patches are used to simulate the linear muscles while the B-spline patches closed in one parametric dimension are employed to imitate the sphincter muscles. Figure 3 shows the two types of muscle patches.

To construct the muscle patch, a mesh of key points is interactively defined on the skin surface which briefly describes the shape of the muscle as well as its fiber orientation. These points are shifted with an inward offset which indicates the distance between the skin and muscle. Through these displaced points, a B-spline patch *S(u,v)* is built by interpolation. The *v* parameter direction approximates the muscle fiber orientation, and intuitively, the transverse parameter dimension *u* indicates the potential wrinkle locations with skin deformation. The attached end of a muscle is fixed inward to the skull while the insertion end is connected outward to the skin surface by springs. Figure 2(b) presents some of the muscle patches designed on a face.



(a)Linear Muscle: Open B-spline Patch (b)Sphincter Muscle: Close B-spline Patch

Figure 3: Muscle Patches

3.2. Muscle Animation

A facial expression is conducted by a set of muscle contractions. All facial muscles except the orbicuris oris are attached to the skull at one end while inserted into the skin fasica at the other end. These muscles are described as linear muscles that pull the skin toward the skeletal attachment points. On the contrary, the orbicuris oris are embedded in the skin soft tissues and draw the skin toward a central point.

Let *S(u,v)* be a muscle patch at the initial time. To simulate the linear muscle contraction, one end of the patch $S(u,v)|_{v=0}$ is inserted to the skin surface while the other end $v=v_{max}$ is attached to the skeleton. Muscle contraction is simulated by adjusting the *v* parameter at each time step. For a relax muscle point *S(u,v)*, the contracted muscle position at time t, $r^t_{muscle}(u,v)$, is represented as,

$$r^t_{muscle}(u,v) = S(u,v') = S(u, v\lambda_t + v_{max}(1-\lambda_t)),\ 0 < \lambda_t \le 1 \quad (1)$$

where λ_t is the muscle contraction rate at current time, which equals *1* at time *0* and reaches minimum at maximum muscle contraction.

To simulate the sphincter muscle contraction, the whole B-spline patch is connected to the skin surface. The muscle contraction is simulated by adjusting the *u* parameter at each time step. The deformed muscle is calculated as,

$$r^t_{muscle}(u,v) = S(u',v) = S(u\lambda_t + u_{max}(1-\lambda_t), v),\ 0 < \lambda_t \le 1 \quad (2)$$

where u_{max} specifies a central region limits the sphincter muscle contraction.

The tension from muscle to skin is simulated by the Hookean spring which connects the skin surface vertices to muscle patches.

4. Biomechanic Skin Model

Different types of models such as geometric models and physically based models are used for skin deformation. In order to produce more accurate skin deformation with wrinkles and provide a potential for medical applications, we employed a biomechanical model. Moreover, a linear plastic model is extended to calculate the permanent skin deformation which provides measures of wrinkle formation due to aging.

4.1. Elastic Membrane Model

Different biomechanical models of skin have been proposed in the literature [Lanir 87]. For our purpose, we consider skin to be biaxial and incompressible. The skin can not support negative stress, and hence buckles easily [Danielson 75].

As skin is thin and quite flexible, a plane stress elastic model is applied for each triangle. Each triangle employs a local coordinate system *(X,Y)* according to skin's biaxial behavior. Generally, the *Y* direction corresponds to the direction of muscle contraction, and *X* to the potential wrinkle. These two directions are usually perpendicular to each other. The potential wrinkle direction of each triangle is obtained by mapping the *u* direction of the closest muscle patch to the skin surface while the muscle contraction direction is set to be vertical to it (see Figure 4).

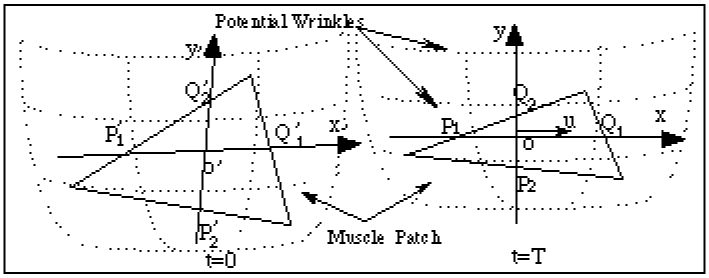


Figure 4: Local Coordinate System for a Triangle

In case of small deformation, any three measurements in the triangle can be used to calculate the components of strain *([epsilon]$_x$, [epsilon]$_y$, [gamma]$_{xy}$)* . Usually, the three measurements are strains along three lines defined on the triangle along the three edges of a triangle. The strain value for a line at an angle [theta] with *X* axis is given as [Timoshenko 82].

$$\varepsilon_\theta = \varepsilon_x \sin^2\theta + \varepsilon_y \cos^2\theta + \gamma_{xy} \sin\theta\cos\theta \quad (3)$$

However, in the case of large deformation, this method is no longer valid and may produce unreasonable deformation. The general theory of large deformation is rather complicated to apply. Nevertheless, the incompressibility of skin simplifies the problem. As the model only supports non-negative stress, skin at a particular region deforms along a rather uniform direction controlled by muscle contractions. Therefore, the shear strain is quite small and the principal strain direction (the direction with no shear strain component) approaches to the potential wrinkle line. We can assume that the potential wrinkle line remains vertical to the muscle contraction direction in the deformed state. In this configuration, we directly calculate the strain components by measuring strain along the coordinate axis.

As the forces are calculated referring to current state, at each step *T*, the coordinate system is first set in the deformed triangle(Figure 4). The *X* direction is set along the potential wrinkle segment P_1Q_1, the *Y* coordinate is set vertical to *X* direction along P_2Q_2 segment which approximates the muscle contraction direction.

At original state, segment $P'_1Q'_1$ is along the potential wrinkle direction, and $P'_2Q'_2$ corresponds to P_2Q_2 respecting that P_1, Q_1, P_2, Q_2 and P'_1, Q'_1, P'_2, Q'_2 separate the edges with the same ratio. The stretch strain components are calculated as,

$$\varepsilon_x = \frac{P'_1Q'_1 - P_1Q_1}{P'_1Q'_1}, \quad \varepsilon_y = \frac{P'_2Q'_2 - P_2Q_2}{P'_2Q'_2} \quad (4)$$

while the shear strain component is obtained by,

$$\gamma_{xy} = \left(\frac{\pi}{2} - \phi\right) / \phi \quad (5)$$

where ϕ is the angle between segments $P'_1Q'_1$ and $P'_2Q'_2$, and $\pi/2$ is the approximation of the angle under the deformed state.

Hook's law is used for computing the stress components on the triangle. To filter the negative stress component, principal stress directions (directions with no shear stress) are computed. Let α be the angle between the principal stress direction and *X* axis, we have the relation:

$$\tan 2\alpha = \frac{2\tau_{xy}}{\sigma_x - \sigma_y} \quad (6)$$

where τ_{xy} is the shear stress component, σ_x and σ_y are normal stress components. The principal stress components are calculated along the two vertical directions [Timoshenko 82]. The negative component is neglected in our model while the other components are then used for calculating the in-plane force along triangle edges. Each edge force is finally distributed to its two vertices. Therefore, the in-plane stress of triangles is finally contributed to the vertices as a force component.

4.2. Plastic Model

Plasticity causes the irreversible atom dislocation and permanent deformation beyond certain force limits. Skin's remaining deflection after the removal of load is the result of plasticity. Shanders [73] proposed a plasto-visco-elastic skin model in which the total deformation is the sum of an initial elastic response, a viscous component and a plastic component. In the case of certain deformations the plastic component linearly depends on the load duration. We extend it to present the sum of plastic deformation after a deformation process,

$$V_p = a\int_0^T V_e(t)dt \quad (7)$$

where V_p is the permanent deformation after animation, $V_e(t)$ is the deformation at time *t* during the animation, *T* is the animation duration. In our model, the plastic deformation is applied to wrinkle bulge height in the synthetic texture image to form wrinkles due to age. We will discuss the modification of texture image in the following section.

5. Wrinkle Simulation

According to the characteristics of the skin, we classify two types of wrinkle models: static and dynamic models[Wu 96]. For the static model we define the shape and form of the wrinkles or other macro lines as geometrical structures on the planar skin surface which do not change with skin deformation. The dynamic wrinkle model is based on the biomechanical skin model and accounts for the changes in the form and shape over time. The following sections present the static and dynamic models.

5.1. Static Model

The physiology of wrinkles demonstrates that one needs to consider the micro and macro structure of the skin surface for modeling the geometrical features of the skin texture. For the static model, the location and the form of the wrinkles or other lines are established on the structure of the skin surface. Real photos hold more skin details including micro and macro structure, which can be used combined with a synthetic skin structure. In the following sections, we describe our method of modeling and rendering the geometrical features in the micro and macro structure of the skin.

5.1.1. Micro Structure

The micro structure appears to be a layered net-structure which is determined by two major factors: the furrow pattern and the ridge shape. A close look at this structure shows a triangular mesh pattern with several layers of furrows. This suggests applying a hierarchical triangulation to a skin region to obtain geometrical patterns for the micro structure. A ridge surface is defined as a function on the triangle base.

The furrow pattern is generated by a Delaunay triangulation [Farin 90] for each skin region. Given the texture image boundary corresponding to the 3D object, the Delaunay triangulation divides the 2D texture image plane into a triangle mesh where the edges represent the furrows. By imposing some conditions such as edge size or angle constraints, different kinds of triangle mesh can be produced.

The ridge shape is defined on the triangle base. The height of the ridge increases while going from the edge to the centre of the triangle. Figure 5 shows a ridge shape model: *C* is the centre of the triangle, *P* is any point inside the triangle, *H(C)* and *H(P)* are their corresponding ridge surface heights. The value of basic shape function *f(P)* is zero at the edge, and reaches unity at the centre. Sharper or flatter bulges can be obtained choosing different shape functions.

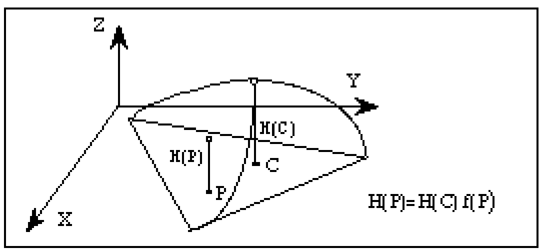


Figure 5: Ridge Shape Model

Micro furrows present a hierarchical structure: there are smaller ridges inside a small ridge. Thus, the Delaunay triangulation is repeated until the desired layer is achieved. The shape function of the hierarchical structure is recursively defined.

Figure 6 shows close up of micro structure rendering using bump texture mapping.

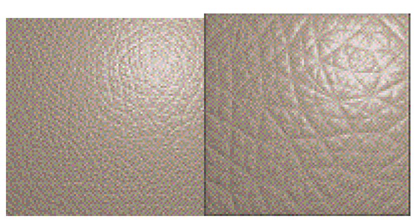


Figure 6: Examples of Micro Structure Rendering

5.1.2. Macro Structure

In addition to micro furrows all over the body, macro furrows such as palm lines and potential flexure wrinkle lines exist in some skin regions. These are modeled as the macro structure. An array of points on the skin model surface is defined interactively to locate the position of the macro furrows. A B-spline curve is then obtained by interpolation or approximation through the defined points. This 3D curve is mapped to a polyline on the 2D texture image using cylindrical or planar projection. As the macro lines are always along the furrows of micro lines, a constraint Delaunay triangulation is employed to generate the skin pattern so that the edges on the micro structure are retained. For more natural visual effects, a random deviation is added to the furrow.

Macro lines bulge between the furrow lines. The bulge region can be defined in the 2D texture image space *(S,T)* as a quadrilateral mesh along the polyline (see Figure 7). The bandsize -- defined as an offset-- of the wrinkle gives its neighboring points along the bulge direction. We use bilinear interpolation parameters *(u,v)* in each quadrilateral to define the bulge function.

The bulge shape is defined as a height function *H* of band width. The *(u,v)* values of an inside point *P* are used as parameters to obtain the height value. The band width for the shape function is computed as the linear distance ratio of *P* along the isoparametric line for a given *u*. Different kind of shape functions can be used for simulating the bulge shape.

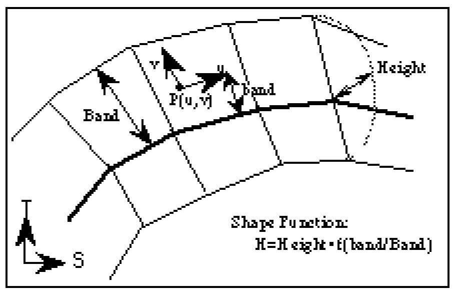


Figure 7: Macro Wrinkle Band

Figure 8 shows some skin rendering examples combined with macro and micro structures with different bulge shape functions.

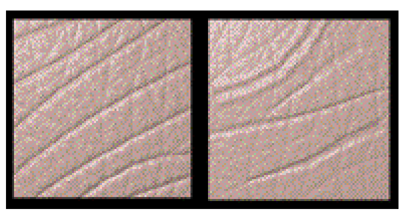


Figure 8: Macro Structure of Skin

5.1.3. Real Photo Image

Real photos capture all skin details including micro and macro structure. Manipulating a 3D model of a face in conjunction with a real photo by texture mapping gives the realism to the character animation. However, the real photo carries only the skin details of the person whose photograph is used. Furthermore, it does not reflect the change of the same human model at different ages. In our model, synthetic texture patterns are combined with the real photo image, adding new features of skin or forming wrinkles due to facial animation or aging.

An interactive tool is used to match features from a 3D face model to a 2D photo image by selecting 3D feature points and projecting them to a 2D photo image. The texture coordinates of other vertices are obtained by using linear interpolation in a triangular domain[Kalra 93].

To apply synthetic texture patterns to the real photo, feature points in the skin surface are projected to the photo image. For a key point inside a triangle of the 3D model, its location in the 2D texture image can be achieved by linear interpolation of the vertex texture coordinates using barycentric coordinates. The synthetic patterns are constructed through the key points in the 2D photo image.

5.2. Dynamic Model

It is quite expensive to geometrically model all the wrinkles on the 3D skin surface. This would require very fine skin surface resolution resulting in enormous computation. Thus, we deform the skin mesh according to the biomechanical model as described, and form the wrinkle bulges by deforming a synthetic bump texture image. The bulge parameters are determined by skin deformation. In the next sub-sections we describe the deformation parameter mapping to the texture image for expressive and aging wrinkles.

5.2.1. Expressive Wrinkles

Expressive wrinkles are usually transverse to the muscle fibers whose actions are active during the facial animation. In our model. They are defined as curves on skin along the potential wrinkle lines which are determined by muscle patches. The wrinkles are then mapped to the texture image as macro line (Section 5.1.2). To get the deformation information, each point on the wrinkle polyline in a texture image has the corresponding triangle reference of the 3D skin surface.

Due to the incompressibility of the skin, under negative strains skin buckles and bulges appear. A simple mapping approach is used for obtaining the appropriate height value for the bulge function from the deformation or strain value *[epsilon]*. Figure 9 shows a line deformed from (a) to (b). The original length is $2l_0$; after deformation it is $2l$, and the deformation d as a bulge can be computed as (assuming linear case for bulge) $l_0^2 = l^2 + d^2$. The height for the bulge function is computed as a function of strain and the bandsize. During the animation, as the strain values change, the height function changes accordingly.

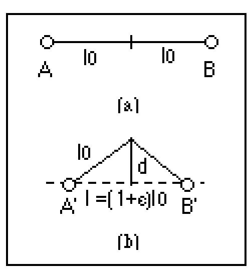


Figure 9: Approximation for the Height of Bulge

5.2.2. Age Wrinkles

Age wrinkles are visible after repeated skin deformation over time. The deformation during facial expression is recorded by the measure of wrinkle bulge *d*. The bulge measure of a permanent wrinkle, d_p, is calculated as the deformation V_p in the plastic model described in Section 4.2,

$$d_p = a \sum_i d_i \Delta t_i \quad (8)$$

where d_i is the bulge height at each step with time duration Δt_i, *a* controls the degree of permanent deformation. The Bulge height function flatter than expressive wrinkles are employed. The bulges around the furrow are more recessed rather than pronounced, while random noises are added to the bulge furrow to obtain natural appearance.

5.3. Rendering

In our model, different skin surface details and their deformations are stored in texture images. This prompts us to use a renderer that supports different types of mapping (color mapping, displacement or bump mapping) and can compose multiple levels of details. RenderMan is chosen because it provides the facility to define our own rendering shaders satisfying the multi-layered texture mappings. BMRT (Blue Moon Rendering Tools) is the specific renderer employed in our animation production[Gritz, WWW site].

We demonstrate our model with some examples. Figure 10 presents a close up of a man and a baby face. It is produced by texture mapping of real photo and synthetic micro structure of different roughness. Figure 11 shows an aged face applying age wrinkle formation after skin deformation.

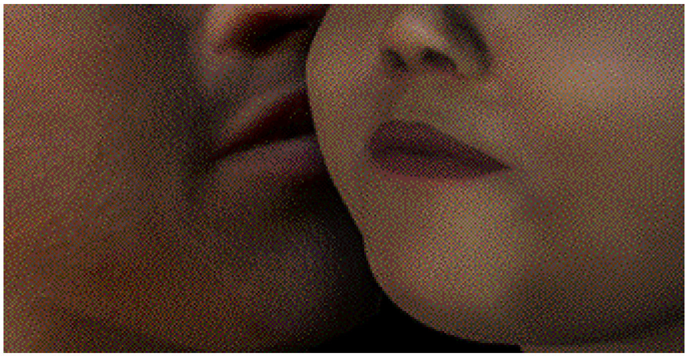


Figure 10: A Man Kisses a Baby

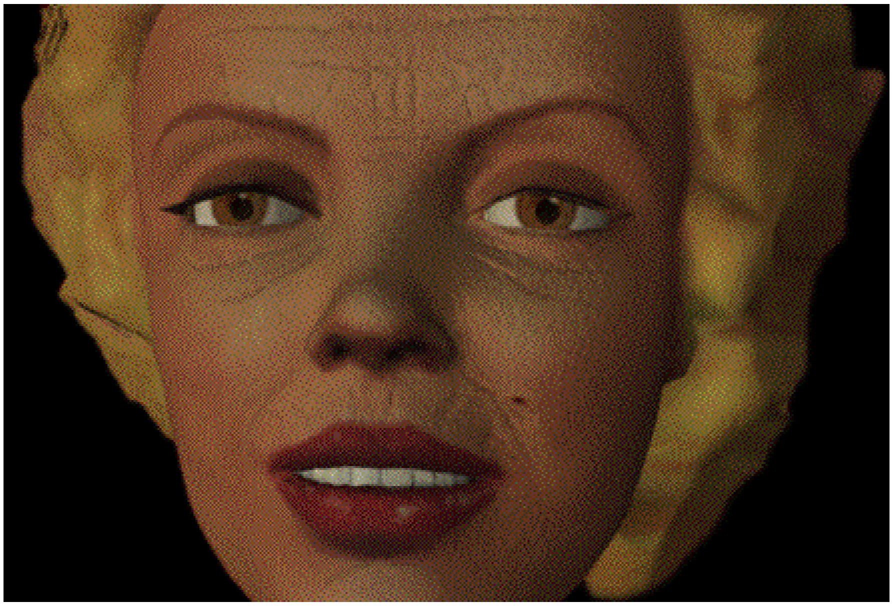


Figure 11: Old Wrinkled Marilyn

6. Conclusion

In this paper we have presented an approach for simulating wrinkles during deformation on human skin. There are three major modules in the whole process: Muscle Design, Skin Deformation and Wrinkle Simulation. In this approach the static model of wrinkles considers the rendering of the geometrical structure and other details of the skin, while the dynamic model employs biomechanical deformation information. The models are applied for different cases: general surface details of skin, expressive wrinkles and aged wrinkles on the face. In the static model, synthetic micro and macro structure are combined with real photos to create realistic pictures. The dynamic model is used for expressive and age wrinkles. As wrinkles are induced by facial animation, they are defined according to the muscle anatomy and contraction. More specifically, the position of the wrinkle is defined on the muscle in its transverse direction. An expressive wrinkle is generated as a direct mapping from muscle patch contraction. The bulge generated along the wrinkle line is decided by the skin deformation during animation. A multi-layered renderer is used to combine different kinds of skin detail in the same region.

Solid modeling of the human body based on actual medical data and a biomechanical skin model with finite element analysis would offer the foundation for wrinkle formation and growth, but it would be computationally intensive. Thus, our approach simplifies the process and combines biomechanical deformations with rendering nuances by layered texture mappings.

Acknowledgment

This research is supported by Le Fonds National Suisse pour la Recherche Scientifique (FNRS). The authors would like to thank Larry Gritz for providing BMRT. We also thank Gael Sannier for useful discussions concerning texture mapping. Many thanks to Nabil Sidi-Yacoub for his help in producing the final rendered images.

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Back Home