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CG Representation of Wood Aging with Distortion, Cracking and Erosion

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Abstract

Materials exposed to the elements change in appearance because of aging. Because wood is an organic substance, cracks and the surface erosion occur easily. To produce realistic computer graphic images, we need simulate the aging phenomenon also. Here, we propose a visual simulation of the distortion, cracking, and erosion of wood. In this method, wood is represented by a tetrahedral mesh. By setting semi-physical variables at each vertex in this mesh, a visual simulation of wood aging can be accomplished. The surface of the wood is defined by values assigned to the superficial tetrahedral mesh vertices. Changes in the surface are achieved by value changes. The effectiveness of this method is demonstrated by applications on a plank and shapes such as a bunny and an armadillo statue.

Key words: Visual Simulation, Wood, Aging, Crack, Erosion.

1 Introduction

Natural factors such as light, wind, water, and biological activity influence exposed objects. The expression of phenomena such as weathering, erosion, corrosion, rust, and dirt can be conducted using computer graphics (CG).

Wood used to make buildings and tools can develop cracks, become stressed by weathering, and attacked by blight. Figure 1 shows an example of aged wood. The causes of wood deterioration are complex and are not completely understood.

Figure 1: Example of aged wood.

Visual simulations of material changes have been reported recently. Dorsey [4] represented a surface as a series of layers, and simulated the patina. Dorsey [3] also represented a surface as a slab structure to simulate weathered stone. These two studies mainly investigated changes on the surface of the materials. Recently, more basic distortions and changes on the surface of the object have been reported. Paquette [7] simulated paint cracking and peeling. Yin [12] proposed a method for simulating phenomena like color variations involved in the weathering of wood. However, these studies investigated changes involving superficial changes of the materials, not major deformation or internal cracks.

Some studies involved visual simulation of cracks in an object. O'Brien [6] used a finite element model to generate cracks in the object with a tetrahedral mesh and simulated animation of the brittle fracture. Cracks initiate and propagate in the object by dividing into multiple tetrahedra. Gobron [5] proposed a 3D surface cellular automata method. First, this method set a simple semi-physical variable on the surface, and then let the crack grow according to this variable. This method can simulate

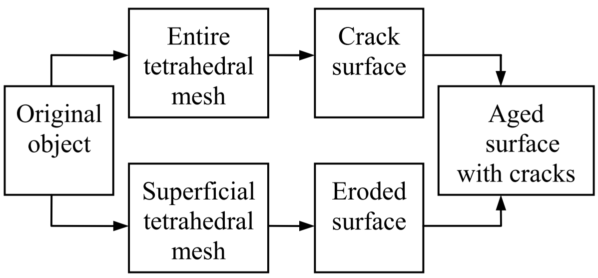

Figure 2: Visual simulation process. *Crack surface* and *Eroded surface* are computed individually, and then combined into *Aged surface with cracks*.

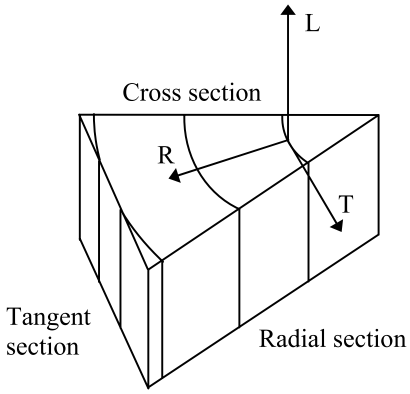

Figure 3: Three main axes L, R and T, and three main sections *Cross section*, *Radial section* and *Tangent section*.

superficial cracks of many materials. In this paper, we efficiently simulate crack surfaces in a 3D object using a semi-physical method.

The visual simulation process of wood changes was divided into two stages, as shown in Figure 2. One simulates distortions leading to cracks in the wood. The other simulates wood surface erosion. The wood is represented with a tetrahedral mesh. To simulate the distortions and cracks, a tetrahedral mesh composed of big tetrahedra was used to decrease the computing cost, which is explained in detail in section 4. To simulate erosion, a superficial tetrahedral mesh composed of small tetrahedra was used, as explained in section 5. Finally, aged wood is obtained from combining the curved surface that shows the crack with the curved surface that shows erosion.

2 Background Knowledge

Many studies have been conducted in the field of wood research (Asano [1], Takahashi [9], Yaga [11]) that supply an introduction to the knowledge of wood.

The cells of a tree trunk are arranged in the direction of the trunk axis and in the radial direction. Therefore, the study of wood requires the consideration of the three main axes of the wood. A tree trunk form in a coordinate system is shown in Figure 3, indicating the three standard directions: trunk axis or fiber direction L, radial direction R that passes through the tree's core, and tangent direction T along the annual ring. The section perpendicular to the trunk axis is designated the cross section. The section parallel to the trunk axis that passes through the tree's core is called the radial section. The section that follows the circumference of the trunk is called the tangential section.

2.1 Distortion and Crack of Wood

The moisture content of the wood varies greatly according to the surrounding temperature and humidity conditions. Cracks occur during the wood drying process. Wood shrinkage shows remarkable anisotropy that is influenced by internal components and organization of the wood. Shrinkage in the tangential direction is largest, approximately 3.5-15%, while shrinkage in the radial direction is 2.4-11%, and in the fiber direction is 0.1-0.9% (Takahashi [9]). Shrinkage differs considerably depending on tree species, the specific gravity, and other factors. In general, the anisotropy of the tangential and radial directions is larger in low specific gravity material.

Wood strength depends on the direction of the cut. Strength weakens in the order of fiber, radial, and tangential direction. In general, when wood dries, the vertical direction of the generated crack surface is in the direction of the tangent. That is, the wood crack occurs along the radial section of the wood.

2.2 Deterioration of Wood

In general, wood deterioration occurs by microbial, water, heat, light, radiation, air, chemical, and mechanical action. Deterioration caused by sunlight, wind, and rain is called weathering. Through weathering, wood first discolors, the soft organization of the surface decomposes, and hard portions of the wood are exposed. Then, small cracks appear that eventually extend across the entire surface, causing fractures at the end of the wood pieces.

3 Tetrahedral Mesh

Many studies utilize a tetrahedral mesh to represent an object (Schöberl [8], Tsuji [10]). In a visual simulation, tetrahedron size uniformity influences the results. To minimize this influence, a tetrahedral mesh with a high degree of uniformity should be employed. In nature, crystal structures with a high degree of uniformity are formed by closely packed spheres in 3D space. Therefore, we constructed a tetrahedral mesh consisting of a closely packed spherical structure.

Figure 4 shows the 3D space created by closely packed spheres. In the first layer (broken line in figure), six spheres are arranged around a single sphere. A sphere in the second layer (solid line in figure) has three adjacent spheres in the first layer. A sphere in the third layer is located in a position different from those in the first and second layers. The structure generated in this manner is called a cubic closely packed structure (Tsuji [10]). If adjacent sphere cores are connected by a line, the 3D space is assembled into a tetrahedron and octahedron. If one octahedron is divided into four tetrahedrons, the space is represented by a tetrahedral mesh.

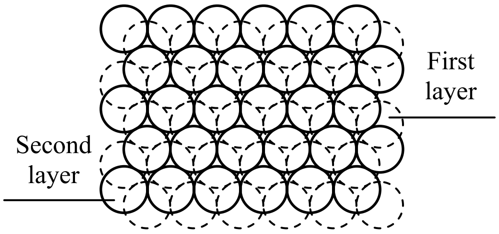

Figure 4: Construction of the cubic closely packed structure. The spheres in the first layer are arranged as broken line and the spheres in the second layer are arranged as solid line. A sphere in the third layer is located in a position different from those in the first and second layers.

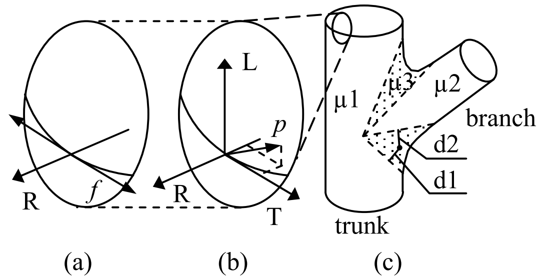

Figure 5: Crack tendency and movement tendency. For the region of trunk (part μ1) and the region of branch (part μ2) in (c), the crack tendency *f* is set according to the tangent direction as shown in (a), the movement tendency *p* is set according to shrinkage of wood as shown in (b). For the region between trunk and branch (part μ3) in (c), the crack tendency and the movement tendency are interpolated from those of μ1 and μ2.

An object is then placed in this space. The tetrahedra inside the object are called the internal tetrahedra. Tetrahedra adjacent to the surface of the object are called superficial tetrahedra. We used this total tetrahedral mesh to simulate distortion of and cracks in wood. The superficial tetrahedral mesh is used to simulate erosion.

4 Visual Simulation of Distortion and Cracks

Wood contain branches. To simulate distortion and cracks, the wood is divided into three regions. Figure 5(c) shows the section that passes through the trunk axis and branch axis. Part μ1 is the region of the trunk, while part μ2 is the region of the branch. Part μ3 is the region between the trunk and branch (shadowed area in figure).

4.1 Movement Tendency and Crack Tendency

Wood is an orthogonal anisotropic material. The shrinkage, mechanical characteristics, and strength of wood are dependent on the three main axes of wood. The character of wood around a knot is especially complex. This study avoids complex computation. Two variables, called movement tendency and crack tendency, are proposed.

The movement tendency is a vector that represents the positional change of each vertex in the wood during distortion. The movement tendency of each vertex in the interior of the wood depends on the shrinkage. When wood dries and shrinks, the shrinkage in the tangential, radial, and fiber directions occurs in a ratio of 10:5:0.5 (Yaga [11]). Therefore, in part μ1 and part μ2, the movement tendency in the coordinate system composed of the tangent, radial, and fiber directions is set to *p* = [10S, 5S, 0.5S], as shown in Figure 5(b). S is a parameter that indicates the size of the distortion. A large value of S indicates a large distortion. Because shrinkage is inversely proportional to humidity in wood (Takahashi [9]), we set the value of S inversely proportional to humidity in wood. Since humidity near the surface of object decreases fast, S value in the area near the surface of object is bigger than the interior of the object. Moreover, because shrinkage in the tangential direction is largest and there is no tangential direction on truck core and branch core, the distortion in the area around the trunk core and branch core is small, so the S values of the area around the trunk axis and branch axis are smaller than the values of the other areas. For part μ3, *p1* represents the movement tendency according to the three main axes of the trunk; *p2* represents the movement tendency according to the three main axes of the branch. Thus, the movement tendency p3 of a vertex in part μ3 is obtained by:

$$p3 = \alpha p1 + (1-\alpha) p2 \qquad (1)$$

where α is a coefficient in the range of 0 to 1. As shown in Figure 5(c), this coefficient is d2/(d1+d2). Here, d1 is the distance from part μ1, and d2 is the distance from part μ2. To obtain a more natural and realistic result, noise is added to the movement tendency determined by expression (1).

The crack tendency is a normal vector of the crack surface generated during wood distortion. Wood generates cracks along the radial section as described in section 2.1. Therefore, similar to *f* shown in Figure 5(a), the crack tendency in part μ1 and part μ2 is set according to the tangent direction. In part μ3, we use *f1* to represent the crack tendency according to the three main axes of the trunk; *f2* represents the crack tendency according to the three main axes of the branch. Then, the crack tendency *f3* of a vertex in part μ3 is obtained by:

$$f3 = \alpha f1 + (1-\alpha) f2 \qquad (2)$$

where α is the same as in expression (1). Noise is added to

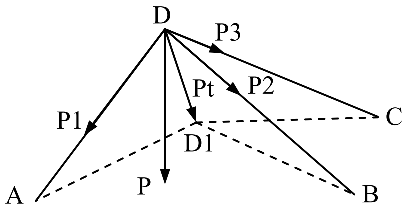

Figure 6: Update of the position of a vertex. Vertex D is moved to position D1 according to the average vector Pt of projection vectors P1, P2 and P3 obtained from original movement tendency P.

the crack tendency obtained by expression (2), which provides the crack tendency of each internal vertex of the wood.

First, the object is distorted according to the movement tendency. Then, cracks are generated where they can occur easily. After a crack is generated, the stress around the crack decreases. Therefore, the crack tendency around the crack surface also decreases. After that, object distortion occurs again and new crack surfaces appear in the tetrahedral mesh according to new crack tendency values. By repeating this process, the distortion and crack surface of the object develops. Finally, the crack tendency of each vertex in the wood is minimized and the wood shape and cracks stabilize.

4.2 Distortion of Wood

The movement of internal wood vertices is influenced by the movement tendency.

The vertex in the tetrahedral mesh is divided into two types: a vertex that has been moved (the fixed vertex), and a vertex that has not been moved (the free vertex). Figure 6 shows an algorithm that moves free vertex D, which becomes fixed vertex D1. Vertices A, B, and C are all fixed vertices adjacent to free vertex D. Vector P is a movement tendency of vertex D, obtained by the method described in section 4.1. The direction of vector P is from free vertex D to fixed vertex D1. Vector P1 is a projection of vector P according to line DA. Vector P2 is a projection of vector P according to line DB. Vector P3 is a projection of vector P according to line DC. The vector Pt of vertex D is obtained by (P1+P2+P3)/n, where n is the number of fixed vertices adjacent to D vertex (n=3 in this case). Free vertex D is moved according to vector Pt, and it becomes fixed vertex D1.

The first fixed vertex is the vertex nearest to center of gravity of the object in a tetrahedral mesh. The free vertex adjacent to this fixed vertex moves according to the movement tendency before becoming a fixed vertex. Next, all of the free vertices adjacent to the fixed vertex move according to the movement tendency before becoming fixed vertices. As this process repeats, all of the vertices of a tetrahedral mesh become fixed vertices. The result is a distorted object.

Because of the anisotropy of wood, the amount of shrinkage along the tetrahedral edge varies during the drying process. Cracks appear to occur easily where shrinkage is most extreme.

4.3 Cracks in Wood

Cracks in wood occur according to the crack tendency of the tetrahedral mesh. A crack surface is generated vertically in the direction of the crack tendency. The magnitude of the crack tendency of the vertex around the crack surface decreases after the crack is generated. If the magnitude of the crack tendency is greater than zero, we say a crack tendency exists. Two positions exist where a new crack can occur: a position of extreme distortion, and the border of a crack that has already been generated.

O'Brien [6] used a tetrahedron division method, which generated a realistic crack shape. This tetrahedron division method is applied here.

The vertex in the tetrahedron where a new crack will occur is called the crack vertex. Figure 7 shows the generation of a crack from the crack vertex in a tetrahedron. The tetrahedron shown in Figure 7(a) has one crack vertex. Vertex A is a crack vertex. Vector f is the crack tendency of vertex A. In this case, crack surface AEF is perpendicular to f and is generated by including vertex A. Vertices E and F are border vertices of the crack surface, and are in a position where a new crack is likely to occur. If a crack tendency of the F and E vertices exists, they become new crack vertices. The tetrahedron shown in Figure 7(b) has two crack vertices. Vertices A and B are crack vertices. Vector f is a crack tendency of vertex A and vector f' is a crack tendency of vertex B. Crack surface ABE is perpendicular to $f+f'$ and is generated by including vertices A and B. If the crack tendency of vertex E exists, vertex E becomes a new crack vertex. The tetrahedron shown in Figure 7(c) has three crack vertices. Vertices A, B, and C are crack vertices. Because vertices A, B, and C are close to one another, the crack tendencies

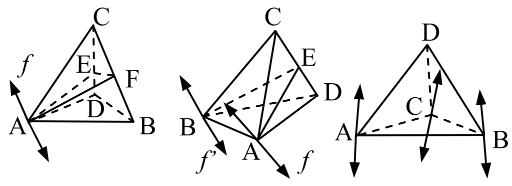

Figure 7: Cracks growing in tetrahedral mesh. Figures (a), (b) and (c) show the three cases where one, two and three crack tendencies are given in one tetrahedron.

of these three vertices are very similar. In this case, the crack surface is plane ABC.

As described by O'Brien [6], a discontinuous tetrahedral mesh is generated because of new edge vertices (such as vertices E and F in Figure 7(a)) that exist after formation of a crack surface. For example, as shown in Figure 7(a), a polyhedron such as that defined by ABDEF, which is not a tetrahedron, can be created. Therefore, if the polyhedron and discontinuous tetrahedron are divided into small tetrahedra, the tetrahedral mesh becomes continuous. Through this process, the generated crack surface becomes the surface of a tetrahedron in the tetrahedral mesh. When the tetrahedron is distorted, the crack surface is also distorted.

Problems can arise when the crack surface is generated by the above-mentioned method. First, as shown in Figure 8(a), when one edge is broken more than once, the crack surface may become discontinuous. Plane AEF is a crack surface contain vertex A. Plane HIJ is a crack surface contain vertex H. Because the directions of the crack tendency of vertex A and vertex H are different, the generated crack surface becomes discontinuous on edge BC. To solve this problem, the positions of the vertices J and E are adjusted to their mean position, resulting in the crack surface including vertex A become plane AMF and the crack surface including vertex H become plane HIM. This restores continuity in the crack surface. A second problem occurs when the crack surface is near a vertex of the tetrahedron. As shown in Figure 8(a), the distance between vertex F and vertex C may be very small, making the tetrahedron in the new generated mesh to be thin. This problem can be avoided by setting a minimum distance between a crack surface and a tetrahedral vertex. A third problem arises when the crack surface grows in a wrong direction, as shown in Figure 8(b). AB is an old crack. A new crack should grow along BC. However, a crack may also grow along BD. A crack along BD is considered ill growth and is called opposite growth. It is necessary to specify the scope within a new crack can develop to prevent opposite growth. The shadowed area in Figure 8(b) represents the scope of new crack growth.

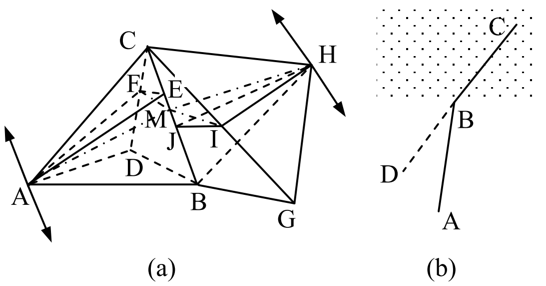

Figure 8: Some problems when crack grow. (a) To get continuous crack surface, vertex E and vertex J are moved to their mean position M. (b) To avoid ill growth direction such as BD, the region in which a new crack can grow is restricted to the shadow region.

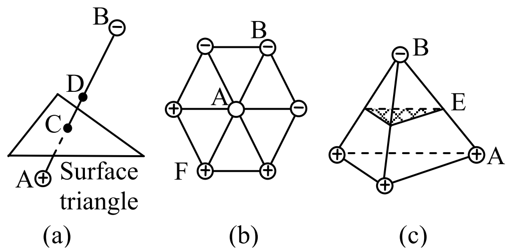

Figure 9: Update of eroded surfaces. (a) Initial values of tetrahedral mesh vertices A and B are set according to the location of intersection C of an original surface triangle with line AB. (b) If the decreased value of vertex A is lower than 0.5, vertex F becomes a plus vertex. (c) An updated eroded surface is determined from the updated values of vertices.

5 Visual Simulation of Erosion

Yin [12] used voxel data for a wood erosion visual simulation. Here, data from the superficial tetrahedron was used to express detail on the surface of the object, for simulated erosion. The vertices of the surface tetrahedron are renewed by decreasing the value of superficial tetrahedral vertices, resulting in exposure of vertices from the interior of the object, thus simulating erosion.

5.1 Erosion Data Structure

The vertex of superficial tetrahedron obtained in section 3 is called a surface control vertex. As shown in Figure 9(a), the triangle is a representation of the object. Vertices A and B are two vertices of the superficial tetrahedron. Such surface control vertices can be classified as minus or plus vertex. Vertex B, which is outside the surface, is a minus vertex; vertex A, which is inside the surface, is a plus vertex. Simulation of surface erosion is possible by changing the values of these two types of vertices.

First, the value of the surface control vertices is determined from the triangular surface area of the original object. As shown in Figure 9(a), vertex C is at the intersection of line AB and the surface triangle. Vertex D is in the middle of line AB. When distance |AC| is smaller than distance |AD|, the value of the plus vertex A is set to 1-0.5|CD|/|AD| and the value of the minus vertex B is set to 0. However, when distance |AC| is larger than distance |AD|, the value of the plus vertex A is set to 1 and value of the minus vertex B is set to 0.5|CD|/|BD|. Several adjacent surface control vertices exist around one surface control vertex. Therefore, the value of one surface control vertex is computed as described above. Then, these values average is determined, which is the original value of the vertex before erosion.

It is possible to convert the surface vertices onto the surface triangles according to the value of the surface control vertex using the method of Doi [2]. This method generates an equivalent value surface from the value of the surface vertex. Concrete coordinates of the surface triangle are obtained by:

$$t = \frac{v_1 - c}{v_1 - v_2} \quad (3)$$

$$Cor = Cor_1 + t(Cor_2 - Cor_1) \quad (4)$$

v_1 is the value of the plus vertex A and v_2 is the value of the minus vertex B; c is the value of equal value surface (0.5 in this case). *Cor* is the coordinate of new triangular vertex E. As shown as Figure 9(c), Cor_1 is the coordinate of plus vertex A and Cor_2 is coordinate of minus vertex B. t is the computed coefficient that represents the relation among the coordinates of vertex A, B, and E. Such conversion has an error margin between the new and original surfaces. The error margin can be minimized by using a smaller tetrahedron, which increases computational accuracy.

5.2 Renewal of Surface Control Vertex

The value reduction method is the same as proposed by Yin [12]. Value changes are computed from the distribution of water on the surface. Where water collects and the density of wood is low, values decrease rapidly. As the value decreases, the surface control vertex and superficial tetrahedron are renewed, and new surface of the object is got, which is the eroded surface.

The renewal algorithm of the surface control vertex is explained by the two-dimensional space shown in Figure 9(b). Vertex A is a former plus vertex. A becomes the minus vertex when the value of vertex A decreases to 0.5 or lower. An internal vertex (vertex F in Figure 9(b)) adjacent to vertex A becomes a plus vertex on the surface. However, if a plus vertex is not adjacent to former minus vertex B, meaning B is a vertex outside of the object, vertex B is removed from the minus vertex group. Thus, the object becomes smaller by renewing a plus vertex and a minus vertex on the surface. This is the process of object erosion.

5.3 Smoothing the Surface

The eroded surface is generated from the data of the plus vertices and the minus vertices by the method described in section 5.1. However, tetrahedral meshes influence the generated surface, and the surface is rough. For better representation, a smoothing computation of the surface is needed. Many smoothing surface algorithms exist, including the simple one used here. The coordinates of a given vertex are adjusted by averaging the coordinates of the surrounding vertices, which results in smoothing of the surface. Because tetrahedral mesh with small tetrahedra is used to simulate erosion, the distance between vertices on the generated surface is small. Therefore, such a smoothness method does not adversely affect surface simulations of the object.

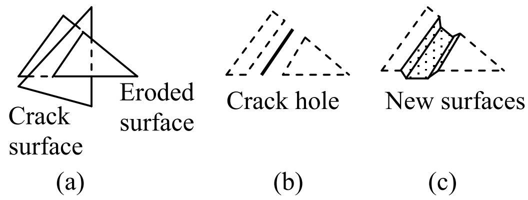

Figure 10: Combination of crack surfaces and eroded surfaces. (a) A crack surface intersects an eroded surface. (b) A crack hole is generated. (c) The crack hole is covered by new surfaces.

6 Combination of Crack Surfaces and Eroded Surfaces

Because wood is composed of fibers, there are fibers in the cracks that develop in wood.

We performed calculations on the crack surface and eroded surface separately as introduction above. The crack is applied on the eroded surface by combining the crack surface and the eroded surface. A part of the crack surface crosses out of the eroded surface, as shown in Figure 10(a). Thus, the part of the crack surface outside the eroded surface must be removed. First, the intersection of the crack surface and the eroded surface is computed. The area of the eroded surface near the cross line is removed as shown in Figure 10(b). The hole representing the crack on the eroded surface is generated. Then, as shown in Figure 10(c), this hole is filled by a new curved surface that is displayed as a gray color indicating shadow. To represent the fibers in the crack, thin curved surfaces are drawn using the same color of the wood. The long direction on these thin curved surfaces is identical to the direction of the fibers.

7 Implementation

This visual simulation was run on a system with an Intel PIII 1.6Ghz CPU, 512 MB memory, and 32MB ATI Rage 128 Ultra display adapter. The wood texture was generated by the method of Yin [12].

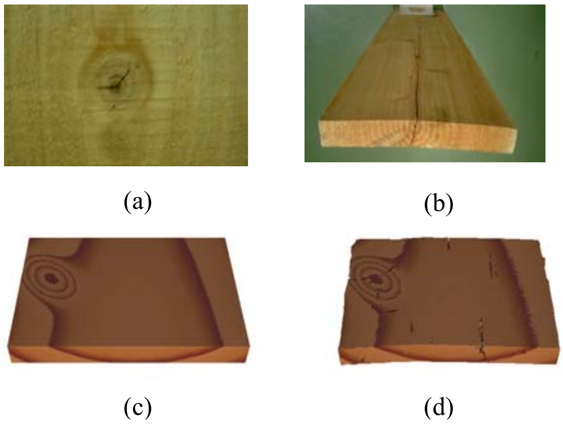

Figure 11: Distortion and cracks in a plank. The images (a) and (b) are photos of a real plank, and (c) and (d) are simulated results.

Figure 11 shows photographs of a wood plank along with visual simulations of the wood plank. (a) is the photo of knot part. (b) is the photo of a plank. (c) is the original model of the plank. (d) is the simulated result of distortion and crack. This wood model was composed of 18,194 tetrahedra. The direction of the rolling of the simulated wood was the same as the real wood. In addition, the crack in the knot developed according to the radial section of the knot. The crack in the trunk developed along the radial section of the trunk; the growth of this crack in the simulation was the same as in the real wood. The computational cost of this method is low, approximately five minutes, and is smaller than other methods (e.g., O'Brien [6]).

Figure 12 shows simulated results of aging process of Stanford bunny. We use Yin[12] method to simulate the change of color. That method uses YIQ color system and decreases the parameter of Y and I to simulate wood color change. The original model is the reconstructed Stanford bunny. The number of tetrahedra in the tetrahedral mesh for crack generation was 11,628. The total number of plus vertices and minus vertices for the erosion simulation was approximately 100 thousand. The results are based on approximately 490 thousand triangles. Figure 12(a) shows the original bunny, while Figure 12(b) shows the bunny after development of a crack and a little color change. Figures 12(c) and 12(d) show the bunny with surface erosion. The object shown in Figure 12(d) is eroded more than that of Figure 12(c). Areas of low wood density are lost first, which is what occurs with real wood. The computational time required for the value decrease and renewal of the surface plus vertex and minus vertex is on the order of tens of seconds. The time of eroded surface generation from surface plus and minus vertices is about 10 minutes for one image.

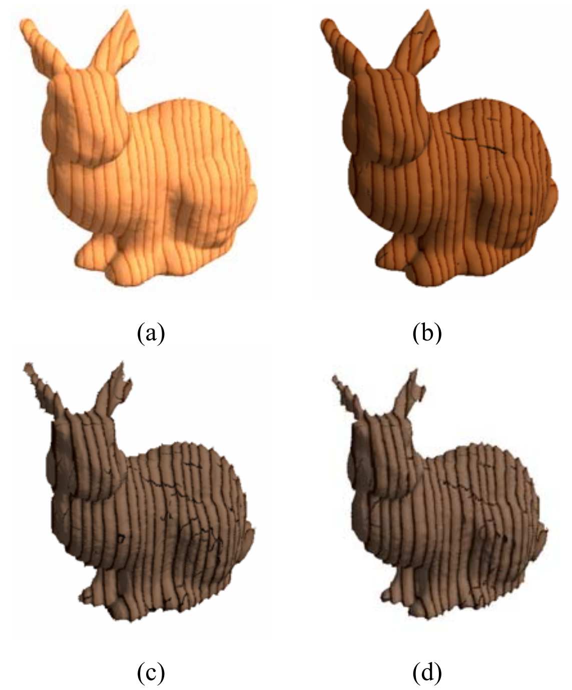

Figure 12: Aging process of Stanford bunny. Image (a) is an original bunny and (b), (c) and (d) are simulated results.

Figure 13 shows the simulated results of complex surface object. The original model is the armadillo statue. The armadillo contains more detailed curved surfaces than does the bunny model. For simulating the distortions and formations of cracks of wood, the influence of a detailed curved surface is small, while the influence from the interior of the object is large. Therefore, the entire tetrahedral mesh with big tetrahedra is used in the visual simulation. For simulating the erosion of wood, the influence of a detailed curved surface is large, while the influence from the interior of the object is small. Therefore, the superficial tetrahedral mesh with small tetrahedra is used to simulate erosion of wood.

8 Summary

We presented a model of distortion, crack formation, and erosion of wood. Using this method, an eroded surface with distortions and cracks similar to real wood can be generated with low computational costs. Future research includes the development of a new wood rendering method that takes the internal organization of wood into consideration. In addition, the visual simulation must consider the influence of living growth such as worm in wood. The method described here was used to simulate only small objects; it is difficult to apply this method to the visual simulation of large objects such as a wooden room. Therefore, new visual simulations should take into account large objects as well. As a future work, it is also interesting to extend our crack model so as to be applicable to other materials.

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(a) (b)

Figure 13: Aging process of armadillo. Image (a) is an original armadillo and (b) is a simulated result.