

Fast Mesh Interpolation and Mesh Expansion with Applications

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Abstract A fast iterative method for constructing a smooth subdivision surface that interpolates the vertices of an arbitrary mesh is presented. The construction is done by iteratively adjusting vertices of the given mesh locally until control mesh of the required interpolating surface is reached. The new interpolation method has not only the simplicity of a local method, but also the capability of a global method in faithfully resembling the shape of a given mesh. The new method does not require solving a linear system, hence it can handle meshes with large number of vertices. Furthermore, the new method is fast and does not require a fairing step in the construction process because the iterative process converges to a unique solution at an exponential rate. Another important result of this work is, with the new iterative process, each mesh (surface) can be expanded as an infinite series of meshes (surfaces) which carry high and low frequency information of the given model. This mesh expansion scheme provides us with new approaches to some classic applications in computer graphics such as texture mapping and morphing. These new approaches are demonstrated in this paper and test results are included.

1 Introduction

Constructing a smooth surface from a set of sampled or scanned data points is an important problem in many areas such as computer graphics, reverse engineering, geometric modeling, computer vision and animation. Interpolation is the most widely used technique in this smooth surface construction process. However, powerful interpolation techniques that have the advantages of both a global method and a local method and, consequently, can handle meshes of any size and any topology while capable of faithfully reproducing the shape of any given mesh are not available yet. In this paper, we try to fill the gap with an iterative interpolation

method. The new method has the advantages mentioned above. Besides, it is very fast and very easy to implement. Subdivision surfaces are the representation scheme used in this interpolation technique.

Subdivision surfaces [1, 12, 15] have become popular recently because of their capability in modeling/representing any complex shape with only one surface [2]. Subdivision surfaces cover both *parametric forms* [13, 14] and *discrete forms*. Parametric forms are good for design and representation and discrete forms are good for machining and tessellation (including FE mesh generation). Therefore we have a representation scheme that is good for almost all applications. Powerful interpolation techniques using subdivision surfaces as a representation scheme certainly are needed for subdivision surface based applications.

Traditional interpolation techniques [3, 4, 5, 6, 9, 10, 11, 16] are mainly aimed at one purpose: *shape reconstruction*. The iterative interpolation technique proposed in this paper, which is an extension of the progressive interpolation technique for B-splines [7, 21], also provides us with a means to look at several classic applications from a different angle and, consequently, allows us to solve these applications with different approaches. This is because with the new technique each mesh (surface) can be expanded as an infinite series of meshes (surfaces). By manipulating this expansion we can control low-frequency and high-frequency information of the given mesh (surface) and, consequently, the overall shape or local details of the mesh (surface).

Overall, the main contributions of this paper can be summarized as follows:

- presenting an iterative interpolation technique that can deal with meshes of any size and topology; the iterative process converges at an exponential rate; the interpolation process does not require a fairing step nor linear system solving.
- showing that each mesh (or surface) can be expanded as an infinite series of meshes (surfaces)

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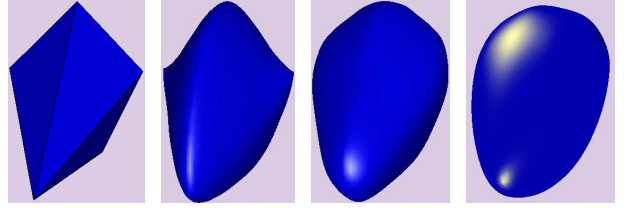
which provides alternative approaches to several classic applications in computer graphics.

The remaining part of the paper is arranged as follows. A brief review of previous techniques in subdivision surface based interpolation is given in Section 2. The basic idea and mathematical derivation of the iterative interpolation and an expansion technique for meshes (surfaces) are presented in Section 3. The fast iterative interpolation technique is discussed in Section 4. Alternative approaches provided by the expansion of a mesh (surface) to applications in texture mapping and morphing are presented in the subsequent two sections. Concluding remarks and future work are presented in the last section.

2 Previous Work

There are two major methods for interpolating a given mesh with a subdivision surface: *local method* [3, 5, 6, 10, 11, 16] or *global method* [4, 9]. In a local method, new vertices are defined as affine combinations of nearby vertices. Interpolating subdivision is the most well-known local interpolation method. In this case, a subdivision scheme such as the Butterfly scheme [3], Zorin et al’s improved version [16] or Kobbelt’s scheme [6], is used to generate the interpolating surface. This approach is simple and easy to implement. It can handle meshes with large number of vertices. However, since no vertex is ever moved once it is computed, any distortion in the early stage of the subdivision will persist. This makes interpolating subdivision very sensitive to the irregularity in the given mesh. When the mesh vertices are dense enough, the undesired artifacts would not be so clear to see. But when the mesh vertices are not so dense, the effect of undesired artifacts becomes obvious on the resulting interpolating surfaces (see Figure 1 for an example where the Butterfly scheme [3], the improved Butterfly scheme [16] and the technique proposed in this paper are compared on a given mesh with five vertices).

A *global method*, on the other hand, usually needs to build a global linear system with some constraints [4]. The solution to the global linear system is a control mesh whose limit surface interpolates the vertices of the given mesh. This approach usually requires some fairness constraints [4] in the interpolation process to avoid undesired undulations. Although this approach seems more complicated, it results in a traditional subdivision surface which resembles the shape of the given mesh more faithfully. The problem with this approach is that it is difficult to handle meshes with large number of vertices.



(a) Given Mesh (b) Butterfly (c) New Butterfly (d) Our Method
Figure 1: Comparing our method (d) with Butterfly (b) and modified Butterfly (c) interpolation method.

There are also techniques that produce subdivision surfaces to interpolate given curves or surfaces that near- (or quasi-)interpolate given meshes [8]. But those techniques are either of different natures or of different concerns, hence will not be discussed here.

As far as we know none of the existing methods has the advantages of both a local method and a global method. Hence we do not have a subdivision surface based interpolation approach that can handle meshes of any size and any topology while capable of faithfully reproducing the shape of any given mesh. Besides, none of the previous techniques were designed for other applications but mesh interpolation.

3 Mathematical Setup

Given a mesh M and a subdivision scheme, our task is to find a smooth subdivision surface to interpolate M . We use the following notations in the paper: \mathbf{A} refers to the matrix that calculates all the limit points of M with respect to the given subdivision scheme; $\mathbf{S}(M)$ refers to the limit surface of M ; $\mathbf{I}(M)$ refers to the subdivision surface that interpolates M and satisfies the property that limit points of its control mesh equal M , i.e., if P is the control mesh of $\mathbf{I}(M)$ then we must have $M = \mathbf{A} * P$. We also assume the subdivision scheme considered here is the Catmull-Clark scheme. Hence, $\mathbf{I}(M)$ and $\mathbf{S}(M)$ are Catmull-Clark subdivision surfaces. However, the techniques presented here work for other subdivision schemes as well.

Let $M = M_0$ be the given mesh. Then the task is to find $\mathbf{I}(M_0)$. If we can find a smooth offset surface \mathbf{L} that moves $\mathbf{S}(M_0)$ to $\mathbf{I}(M_0)$ everywhere, i.e.,

$$\mathbf{L} + \mathbf{S}(M_0) = \mathbf{I}(M_0) \quad (1)$$

then the interpolation problem is solved. The question is: how should \mathbf{L} be constructed?

Note that the above definitions and the fact that \mathbf{A} is invertible (see Appendix B) imply that $\mathbf{S}(M_0) = \mathbf{I}(\mathbf{A} * M_0)$, and $\mathbf{I}(\cdot)$ is a linear operator. Hence \mathbf{L} can

be regarded as an interpolating surface $\mathbf{I}(M_1)$ where

$$M_1 = M_0 - \mathbf{A} * M_0$$

is the difference between M_0 and its limit points $\mathbf{A} * M_0$. M_1 has the same topology as M_0 . Hence $\mathbf{I}(M_1)$ and $\mathbf{I}(M_0)$ can be constructed exactly the same way.

By iteratively repeating the above process we get a sequence of meshes M_i such that

$$\begin{cases} M_{i+1} = M_i - \mathbf{A} * M_i \\ \mathbf{I}(M_{i+1}) + \mathbf{S}(M_i) = \mathbf{I}(M_i) \end{cases} \quad (0 \leq i \leq \infty) \quad (2)$$

From the above equation we have

$$\mathbf{I}(M) = \sum_{i=0}^n \mathbf{S}(M_i) + \mathbf{I}(M_{n+1}). \quad (3)$$

We can also easily get M_i as follows

$$M_i = (\mathbf{E} - \mathbf{A})^i M, \quad (4)$$

where \mathbf{E} is an identity matrix. It can be proven (see Appendix C) that $\lim_{i \rightarrow \infty} M_i = \mathbf{0}$. As a result, $\mathbf{I}(M_i)$ approaches $\mathbf{0}$ when i tends to ∞ . In addition, because subdivision is a linear process, we have $\sum \mathbf{S}(M_i) = \mathbf{S}(\sum M_i)$. Therefore, if we let P be the control mesh of the interpolating surface $\mathbf{I}(M)$, i.e., $\mathbf{I}(M) = \mathbf{S}(P)$, then

$$P = \sum_{i=0}^{\infty} (\mathbf{E} - \mathbf{A})^i M. \quad (5)$$

On the other hand, because \mathbf{A} is invertible (see Appendix B), it is easy to see that $\mathbf{A}^{-1} = \sum_{i=0}^{\infty} (\mathbf{E} - \mathbf{A})^i$. Hence P is indeed the only mesh (having the same topology as M) whose limit surface interpolates the given M . Consequently a fairing process is not needed in the construction of the interpolating surface because there exists only one such surface that interpolates the given mesh. Traditionally, people tried to directly find $\mathbf{A}^{-1}M$ by solving a linear system [4, 9]. It is difficult to deal with meshes with large number of vertices that way. With the new technique, P can be constructed not by solving a linear system, but by iteratively applying eq. (7) until some given error tolerance is reached (see Section 4). Hence there is no problem to deal with meshes with large number of vertices.

More importantly, just like Fourier transform, any mesh (or surface) now can be expanded as an infinite series of meshes (or subdivision surfaces). For example, a given subdivision surface $\mathbf{S}(M)$ can be represented as an infinite series of subdivision surfaces as

$$\mathbf{S}(M) = \mathbf{I}(\mathbf{A} * M) = \sum_{i=0}^{\infty} \mathbf{S}((\mathbf{E} - \mathbf{A})^i * \mathbf{A} * M)$$

and for a given mesh M , we have

$$M = \sum_{i=0}^{\infty} (\mathbf{E} - \mathbf{A})^i * \mathbf{A} * M. \quad (6)$$

In the above infinite series, each term $(\mathbf{E} - \mathbf{A})^i \mathbf{A} M$ contains part of the information on M . Terms with smaller indices contain more information on the overall shape of M while terms with bigger indices contain more subtle details on the shape of M . They can be regarded as low and high frequency information on mesh M . Hence the above two equations transform a space domain model into a frequency domain representation. Because each term itself is a mesh (or surface), it can be furthermore expanded using the above two equations to obtain more subtle details of the original model. Like Fourier transformation, this representation can be used for applications in other areas of graphics and modeling, such as fairing, smoothing, sharpening, low pass or high pass filtering etc. For example, for any $n < \infty$, $\sum_{i=0}^n (\mathbf{E} - \mathbf{A})^i \mathbf{A} M$ gives us a smoother model than M , and the smaller of n , the smoother of the resulting model. On the other hand, $\sum_{i=0}^n (\mathbf{E} - \mathbf{A})^i M$ sharpens model M , and the bigger of n , the sharper of the resulting model. In the following sections, several direct and straightforward applications of the above representation will be discussed.

4 Fast Iterative Interpolation

Eq. (5) should not be used to construct the interpolating surface directly, because it requires costly matrix multiplications. Actually there is no need to compute the matrix \mathbf{A} in the construction of the interpolating surface. Note that if we define $P_n = \sum_{i=0}^n (\mathbf{E} - \mathbf{A})^i M$, $0 \leq n < \infty$, then through simple algebra we have

$$P_{n+1} = P_n + M - \mathbf{A} * P_n. \quad (7)$$

One can use eq. (7) to find the control mesh $P = P_{\infty}$ of the interpolating surface iteratively; $\mathbf{A} * P_n$ can be calculated locally according to the selected subdivision scheme (see Appendix A). Hence matrix \mathbf{A} is not needed in the iterative process. In addition, as we mentioned above, P is the only mesh that has the same topology as M and whose limit surface interpolates M . Therefore there is no need for a fairing process either. Traditional interpolation techniques [4, 9] need a fairing process because extra vertices are added in the interpolation process. These extra vertices, with possibly improperly assigned positions, lead to undulations in the interpolating surface because they need to be interpolated as well.

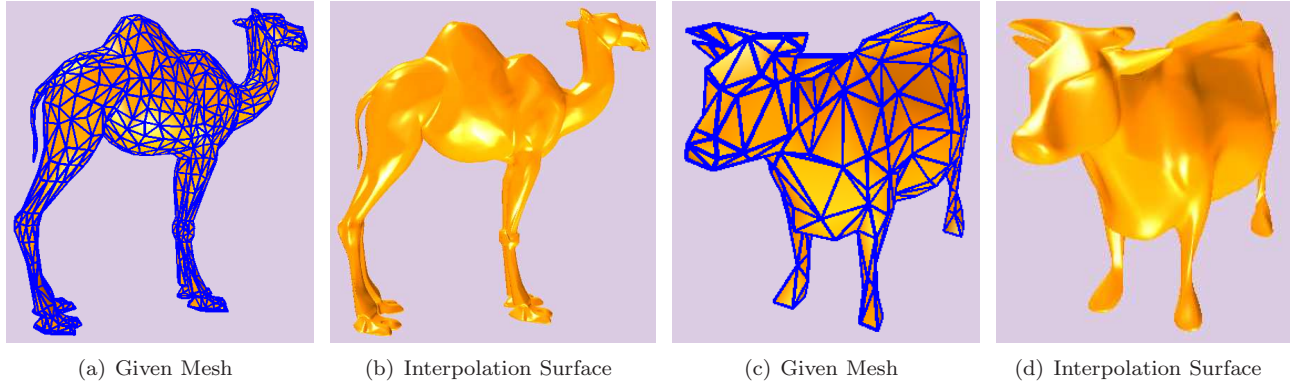


Figure 2: Examples of mesh interpolation.

The computation from P_n to P_{n+1} in eq. (7) is a local affine combination process. Hence this is a local method. On the other hand, P_n converges to $A^{-1}M$, which means every vertex in M contributes to all the vertices in P_∞ . Hence this is a global method as well. Consequently, we have a method that not only has the simplicity of a local method, but also has the capability of a global method in faithfully resembling the shape of a given mesh.

As is proven in the Appendix C, eq. (7) converges at an exponential rate. Hence good interpolation results can be obtained in just a few iterations. Nevertheless, error can be explicitly calculated as $\|M - A * P_n\|$ and the iteration stop criterion can be determined based on some given error tolerance. Because it converges very fast, the new interpolation technique is even suitable for interactive shape design. Figure 2 shows some test results. We can see from these examples that smooth and visually pleasant interpolation shapes can be obtained for complicated meshes with dense or not-so-dense vertices. All the test cases are done in less than one second.

5 Procedural Texture Mapping

3D Procedural texture mapping, instead of looking up an image to do the mapping, generates texture for a model by assigning different colors to vertices of the model. The color of each vertex is determined only by the vertex's location in 3D space. Procedural texture mapping usually uses the Perlin noise [22] function to make rendered models interesting by adding irregularity to a procedural texture. A key component in the construction of Perlin noise is the interpolation function which makes it possible to smoothly add discrete noises of different amplitudes and frequencies together

[22]. Traditionally, in 3D case, Perlin noise is constructed at each integer lattice point in a 3D array, such as the case of solid texturing [24] or hypertexture [23]. As far as we know procedural texture mapping has never been applied to smooth subdivision surfaces by directly assigning colors to points of the surfaces to generate natural-looking models. We believe the main reason of this is because a powerful technique that can smoothly interpolate all the noises of an irregular mesh is not available yet. With the fast iterative interpolation technique presented in the above section, this is no longer the case. We can now do procedural texture mapping on a given 3D model by mapping the model's 3D locations directly into colors. Hence a 3D array for storing noises is not needed any more.

For any given 3D mesh G_0 , perform n times of subdivision to get $n + 1$ meshes G_i , ($0 \leq i \leq n$). For each G_i , a Perlin noise value $\frac{1}{2^i} f(2^i x, 2^i y, 2^i z)$ is generated for each vertex with position (x, y, z) , where f is a random noise function. Note that G_{i+1} has many more vertices than G_i , hence the distribution of noises on G_{i+1} is denser than G_i . All the noises of mesh G_i form a mesh N_i . N_i has the same topology as G_i , and the x component of each N_i 's vertex is set to the noise value at the corresponding vertex of G_i . N_i 's y and z components are not needed, hence these values do not have to be defined. By applying our fast iterative interpolation technique to N_i , we get $\mathbf{I}(N_i)$. Because all $\mathbf{I}(N_i)$ are smooth subdivision surfaces, they can be added together (through subdivision or parametrization [13]) to form a new surface. Let $\mathbf{N} = \sum_{i=0}^n \mathbf{I}(N_i)$. After normalization, \mathbf{N}_x , which is the x component of \mathbf{N} , contains noises for the subdivision surface $\mathbf{S}(G_0)$ everywhere. For a given list of colors, three B-splines $\mathbf{B}(t) = (B_r(t), B_g(t), B_b(t))$ are constructed to interpolate all the colors of the given list. Now one can render $\mathbf{S}(G_0)$ by assigning colors (procedural texture)

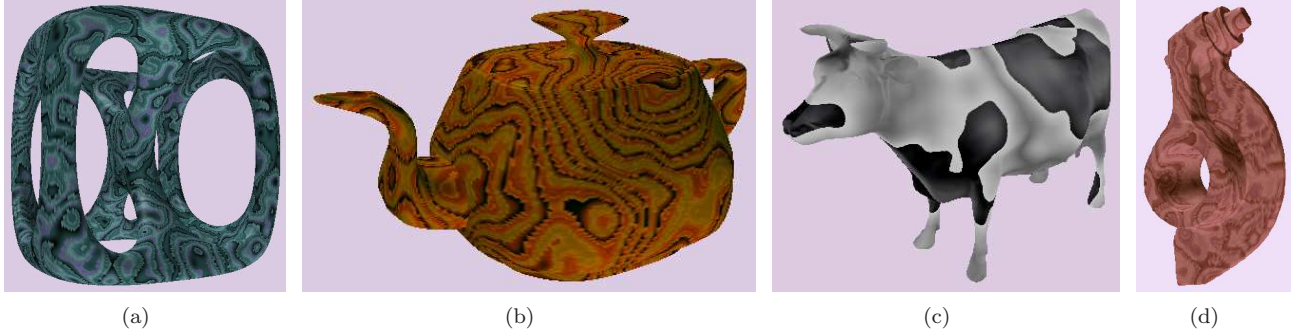


Figure 3: Examples of procedural texture mapping.

to all points of the surface. The color of each point \mathbf{P} of $\mathbf{S}(G_0)$ is obtained by finding the spline values $\mathbf{B}(t_p)$, where t_p is the noise value \mathbf{N}_x at point \mathbf{P} . One can also render mesh G_i directly by assigning generated colors to vertices of G_i only.

Different from methods that only generate Perlin noises at given vertices, The new method can generate more noises of different amplitudes and different frequencies for irregular models at more positions, and can blend them smoothly by interpolation. As a result, it creates procedural texture with better visual effect. More importantly, a huge array is not needed in the procedural texture mapping process. Figure 3 shows several examples of procedural texture mapping generated using our method. All of them are generated with only basic Perlin noise functions.

6 Morphing

For two given meshes M and Q , the task here is to find a smooth transition from Q to M . We assume M and Q have the same topology. If this is not the case, simply resample them using one of the resampling techniques such as [20].

According to eq. (6), we have

$$Q = M + \sum_{i=0}^{\infty} (\mathbf{E} - \mathbf{A})^i \mathbf{A} (Q - M).$$

$(Q - M)$ can be regarded as the difference of the two models, hence our goal is to transform this difference smoothly so that it approaches zero eventually. By taking different finite terms in the above summation, we get a transition from M to Q . However, this approach would not give us a smooth morphing from M to Q because, as we mentioned above, $(\mathbf{E} - \mathbf{A})^i$ shrinks at an exponential rate.

Let $Q_0 = Q$ and for a given $m > 0$, define Q_k recursively as follows:

$$Q_{k+1} = M + \rho \sum_{i=0}^m (\mathbf{E} - \mathbf{A})^i \mathbf{A} (Q_k - M), \quad (8)$$

where $0 < \rho \leq 1$ is used to control the morphing speed. The smaller of ρ , the faster the morphing from Q to M . When $m < \infty$, $(Q_{k+1} - M)$ is a smoother version of $(Q_k - M)$. Similar to the discussion in the above section, we know $(Q_k - M)$ approaches zero when k tends to infinity. As a result, eq. (8) provides us with a sequence of meshes Q_k , $k \geq 0$, transforming Q to M . For a properly selected m and ρ in the above equation for each k , the sequence of meshes Q_k provides a smooth morphing from Q to M .

In the morphing process, Q_{k+1} gets its information from both M and Q_k . The bigger of k , the more information from M . Therefore, eq. (8) can be regarded as a linear operation on meshes M and Q_k .

Traditionally, given two meshes M and Q with the same topology, morphing is done simply by performing a linear operation on M and Q : $u * Q + (1 - u) * M$. This single-vertex-based linear combination method sometimes does not produce meaningful and desired morphing results if features of the meshes are not aligned properly. For example, if M and Q are symmetric about the x -axis, then the morphing process will produce a flat shape when $u = 0.5$ that certainly is not desired. Eq. (8) provides an alternative approach for morphing, which can be regarded as a multiple-vertex-based linear combination process. The bigger of k , the more vertices of Q_0 are involved in determining vertex positions of Q_k . Therefore, the morphing process is not so heavily affected by features of the meshes. Consequently, eq. (8) produces better morphing results than simple linear morphing methods, especially when mesh features are not very well aligned.

Again, eq. (8) should not be used to do the morph-

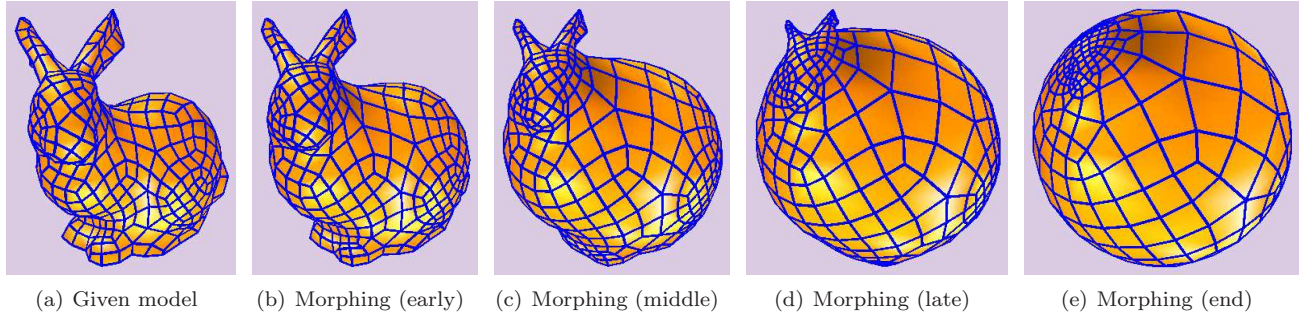


Figure 4: Examples of mesh morphing.

ing directly because of costly matrix multiplications. A formula similar to eq. (7) should be derived for local and iterative computation of the morphing. Figure 5 shows a morphing example of a bunny to a 3D sphere using the technique presented above. As can be seen from this example, the morphing process is very smooth, un-natural looking artifacts usually found in a simple-vertex-based morphing process are nowhere around.

7 Summary and Future Work

An iterative mesh interpolation method and an accompanying mesh expansion technique with its applications in several classic areas of computer graphics are presented. The iterative mesh interpolation method generates a subdivision surface to interpolate a given mesh by iteratively modifying vertices of the given mesh locally until control mesh of the required interpolating surface is reached. The new interpolation method not only has the simplicity of a local method, but also has the capability of a global method in faithfully resembling the shape of a given mesh. Besides, the new method is fast and does not require a fairing step in the construction process of the interpolating surface. Hence, an iterative method seems to be the ultimate solution for mesh interpolation because it has all the advantages one would like to see for a mesh interpolation process.

The mesh expansion technique expands a given mesh (surface) into an infinite series of meshes (surfaces) which can be regarded as high or low frequency information of the given mesh. Hence we can use items of the expansion to control high-frequency and low-frequency information of the mesh (surface) and, consequently, overall shape or local details of the mesh (surface). Manipulating or balancing such pieces of information is a core work in many classic areas of

computer graphics. Hence, a mesh expansion provides a new solution or an alternative solution to some of the classic areas of computer graphics. As far as we know this is the first ever attempt to use a mesh expansion to solve problems in texture mapping and morphing.

One of our future research subjects is to investigate other possible applications of the mesh expansion. Areas that will be considered include mesh compression, feature identification and mesh simplification etc. Another subject of our future research is to compare the performance of the approaches provided by a mesh expansion with other methods in the literature to study their effectiveness and possible improvements. In addition, the matrix A in eq. (6), instead of being a subdivision matrix, could be set to other matrices, as long as their eigen values are in $(0, 1]$. Hence it is possible to design an A and use eq. (6) to solve problems in computer graphics with specified requirements.

Appendix

A Construction of Matrix A

The matrix A is not needed in the implementation. We show it here only for proof purpose. The matrix shown here is for the generalized Catmull-Clark subdivision scheme. The matrix for other schemes can be constructed similarly.

For generalized Catmull-Clark subdivision scheme, new face points and edge points are calculated the same way as the standard Catmull-Clark subdivision scheme, but the new vertex points are calculated differently, using the following formula

$$\mathbf{v}' = \frac{n-2}{n}\mathbf{v} + \frac{1}{n^2} \sum_{j=1}^n (\alpha \mathbf{v} + (1-\alpha)\mathbf{E}_j) + \frac{1}{n^2} \sum_{j=1}^n \mathbf{f}_j$$

where $0 \leq \alpha \leq 1$ and \mathbf{f}_j are new face points after one subdivision. When $\alpha = 0$, we get the standard

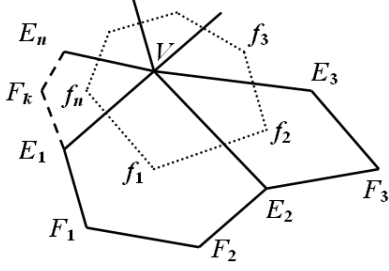


Figure 5: Vertex \mathbf{V} and its neighboring vertices.

Catmull-Clark subdivision scheme. The limit point [4] of a vertex \mathbf{V}_i of degree n_i can be calculated as:

$$\mathbf{V}_i^\infty = \frac{1}{n_i(n_i + 5)} (b_{ii}\mathbf{V}_i + \sum_j b_{ij}\mathbf{E}_j + \sum_j b_{ij}\mathbf{F}_j)$$

where

$$\begin{aligned} b_{ii} &= (n_i - 1)n_i + n_i\alpha + \sum \frac{4}{d_{ij}} \\ b_{ij} &= (2 - \alpha + \frac{4}{d_{ij}} + \frac{4}{d_{ji}}), \text{ if } (\mathbf{V}_i, \mathbf{V}_j) \text{ is an edge} \\ b_{ij} &= 4/d_{ij}, \text{ if } (\mathbf{V}_i, \mathbf{V}_j) \text{ is a diagonal line of a face} \\ b_{ij} &= 0, \text{ if } \mathbf{V}_i \text{ and } \mathbf{V}_j \text{ do not belong to the same face} \end{aligned}$$

Note that in the above formula the surrounding faces could be not-four-sided (see figure 5). d_{ij} is the number of sides of the face of which $(\mathbf{V}_i, \mathbf{V}_j)$ is an edge or a diagonal line. Note that d_{ij} and d_{ji} could have different values because faces adjacent to the edge $(\mathbf{V}_i, \mathbf{V}_j)$ could have different number of sides. But if $(\mathbf{V}_i, \mathbf{V}_j)$ is a diagonal line of a face, then $d_{ij} = d_{ji}$. According to the above definition, we have

$$A_{ij} = \frac{1}{n_i(n_i + 5)} b_{ij}.$$

B A's eigen values $\lambda_i \in (0, 1]$

It is easy to verify that each entry of A is non-negative and the sum of each row equals one. Hence all eigen values λ_i of A are all ≤ 1 . Therefore, to prove $\lambda_i \in (0, 1]$, we only need to show that all A 's eigen values are positive. A common coefficient $1/n_i/(n_i + 5)$ can be factored out for each row of A . If we define matrix B as $B_{ij} = b_{ij}$, then it is easy to verify that B is symmetric, and $A = \text{diag}(1/n_i/(n_i + 5)) * B$. Hence we just need to prove all the eigen values of B are positive, which is equivalent to prove that B is positive definite.

We need to show $\mathbf{X}^T \mathbf{B} \mathbf{X} > 0$ for any non-zero vector \mathbf{X} . $\mathbf{X}^T \mathbf{B} \mathbf{X}$ can be expanded as follows.

$$\mathbf{X}^T \mathbf{B} \mathbf{X} = \sum_{\text{all } E} 2b_{ij}x_i x_j + \sum_{\text{all } D} 2b_{ij}x_i x_j + \sum_i b_{ii}x_i^2$$

$$\begin{aligned} &= \sum_{\text{all } E} (b_{ij} - \frac{4}{d_{ij}} - \frac{4}{d_{ji}})(x_i + x_j)^2 + \sum_{\text{all } F} \frac{4}{d_{ij}}(x_i + x_j + \dots + x_p)^2 \\ &+ \sum_i (b_{ii} - \sum_{(\mathbf{V}_i, \mathbf{V}_j) \in E} (b_{ij} - \frac{4}{d_{ij}} - \frac{4}{d_{ji}}) - \sum_{(\mathbf{V}_i, \mathbf{V}_j) \in E} \frac{4}{d_{ij}})x_i^2 \\ &\geq \sum_{\text{all } E} (2 - \alpha)(x_i + x_j)^2 + \sum_i (n_i^2 - 3 * n_i + 2n_i\alpha)x_i^2 \end{aligned}$$

where E denotes all edges, D denotes all diagonal lines of all faces and F denotes all faces of the given mesh. Let $\sigma_i = n_i^2 - 3 * n_i + 2n_i\alpha$. Because when $n_i \geq 3$, $\sigma_i \geq 0$ and $2 - \alpha > 0$, to prove $\mathbf{X}^T \mathbf{B} \mathbf{X} > 0$, we just need to show $\sigma_i > 0$. Obviously, when $n_i \geq 4$, we have $\sigma_i > 0$. Hence B is positive definite. Also we can claim that B is positive definite if there exists at least one vertex \mathbf{V}_k in the given mesh such that $n_k \geq 4$. This can be proven by contradiction. Suppose this is not the case, then there exists an $\mathbf{X} \neq 0$ such that $\mathbf{X}^T \mathbf{B} \mathbf{X} = 0$. It is easy to see that $x_k = 0$ for otherwise we would have $\mathbf{X}^T \mathbf{B} \mathbf{X} \geq \sigma_k x_k^2 > 0$. In addition, all x_j where $(\mathbf{V}_k, \mathbf{V}_j)$ is an edge must be 0 as well because otherwise we have $\mathbf{X}^T \mathbf{B} \mathbf{X} \geq (2 - \alpha)(x_k + x_j)^2 = (2 - \alpha)x_j^2 > 0$. Similarly, all vertices directly or indirectly connected to \mathbf{V}_k are all equal to 0. Because M is a connected mesh, all x_i are 0, which contradicts the assumption $\mathbf{X} \neq 0$. Hence if there exists at least one vertex whose valance is bigger than 3, then B is positive definite as well.

When all n_i are 3 in a mesh and $\alpha = 0$, B might not be positive definite. However, we can change the value of α to convert the standard Catmull-Clark subdivision scheme into a general Catmull-Clark subdivision scheme, such that B is positive definite. It is easy to verify that when $\alpha > 0$ and $n_i \geq 3$, we have $\sigma_i > 0$. Therefore let $\alpha \in (0, 1]$, say $\alpha = 0.5$, then B becomes positive definite.

Because B is positive definite, all the eigenvalues of A are positive. Therefore A is invertible and all its eigenvalues are in $(0, 1]$.

C Proof of Convergence

Because all eigenvalues of A are $\in (0, 1]$, all the eigenvalues of $(E - A)$ are $\in [0, 1)$. Hence $(E - A)^i$ converges to $\mathbf{0}$ when i tends to infinity. As a result, $\sum_{i=0}^n (E - A)^i$ converges to A^{-1} when n tends to infinity.

It can also be proven that eq. (7) or eq. (5) converges at an exponential rate. To prove this it is sufficient to show that $\|P_\infty - P_n\|$ converges to $\mathbf{0}$ at an

exponential rate.

$$\begin{aligned}
& \|P_\infty - P_n\| \\
&= \left\| \sum_{i=n+1}^{\infty} (E - A)^i M \right\| \\
&= \|(E - A)^{n+1} * A^{-1} * M\| \\
&= \|\mathbf{X}\Lambda^{n+1}\mathbf{X}^{-1} * A^{-1} * M\| \\
&\leq \|\Lambda^{n+1}\| * \|\mathbf{X}\| * \|\mathbf{X}^{-1}\| * \|A^{-1}\| * \|M\| \\
&= \|\Lambda^{n+1}\| * c
\end{aligned}$$

where c is a constant and Λ is the diagonalized matrix of $(E - A)$. Suppose the biggest eigenvalue of matrix $(E - A)$ is λ , then $\|\Lambda^{n+1}\| \leq \lambda^{n+1}$. As we know, $0 \leq \lambda < 1$. Hence we have

$$\|P_\infty - P_n\| \leq c * \lambda^{n+1},$$

which means P_n converges to P_∞ at an exponential rate.

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