International Journal of Hybrid Information Technology
Vol. 9, No.12 (2016), pp. 1-10
http://dx.doi.org/10.14257/ijhit.2016.9.12.01

Solid Texture Synthesis and Mapping of Liver for Virtual Surgery

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Abstract

In order to see clearly the details inside the liver and enhance the users' visual presence in the virtual surgery simulation system, the principles and methods of solid texture are used to render the photorealistic liver. Firstly, the sample sets are processed and multiple samples are used to synthesize the liver solid texture. Secondly, to improving the mapping efficiency of graphics hardware, the texture atlas is used to map the solid texture. In order to improve the fill rate of texture atlas, the height descending triangle bounding box method is used. The experimental result shows that the internal texture can be observed clearly. The study is of great significance to the photorealistic rendering of virtual liver surgery system, and provides a guideline for the solid texture synthesis and mapping of other human organs.

Keywords*: Virtual surgery, Liver, Solid texture synthesis, Solid texture mapping*

1. Introductions

The virtual surgery system is a virtual reality system which is built by the application of computer graphics, computer vision, medical science, biomechanics and sensors technologies, and is used by surgeons to perform the surgery simulations. Operators can get the information of liver model in the scene from visual feedback. Therefore, it becomes an important subject in the surgery simulation on how to get a more vivid and intuitive images [1, 2]. Apart from the usual realistic rendering, topology changes (*e.g.* the topology changes of the liver model in cutting simulation) and geometric deformation (*e.g.* the displacement of nodes in tensile deformation and compressive deformation) could appear in the process of surgery simulation. Thus, how to draw the realistic images including the deformation of the research object, allowing real-time interaction is the main problem in the rendering of the surgery simulation [3].

Based on the processed object, the realistic real-time rendering algorithms can be classified into two types: the geometry-based rendering and the image-based rendering [4]. From the perspective of texture space, the textures can be divided into 1D textures, 2D textures and solid textures [5]. The solid texture generation methods can be further divided into the process-based methods and the sample-based methods, both of which have some limitations [6-9].

The solid texture generated by the traditional method, which is targeted at the actual texture to construct a special texture function, is to generate 3D solid texture space by simulation of the physical forming process. If one has to deal with new texture or if the structure and color of the texture changes, the parameters of the method need to be adjusted. However, in many cases, the effective parameters may be unavailable, which is particularly difficult in the simulation of the existing textures.

The sample-based solid texture synthetic methods cannot generate solid texture which is similar to the specified sample, and are mainly used to synthesize the internal texture of the natural materials, such as the wood and stone, the texture of which has the specific direction in 3D space. The sample-based solid texture synthetic method costs as long as

ISSN: 1738-9968 IJHIT

several quarters to synthesize the solid texture of 128×128×128 in a single common computer. With the increase of dimensions of solid texture, the time in synthesizing increases sharply and the necessary storage space also increases.

Currently available solid texture synthetic methods are not suitable for the virtual surgery system. This project is to propose a new solid texture synthetic method based on the previous research results. The solid texture is constructed with the reference to the digitized visible human body dataset and other medical phantom database; the personalized characteristics of the liver pipeline and lesions are selected from the patients' medical images; and the sample solid texture is reused based on the personalized characteristics to automatically or semi-automatically synthesize the solid texture.

2. Synthesis of Liver Solid Texture

Based on the model's internal texture construction method, solid texture synthetic methods are divided into boundary-independent method and boundary-correlation method [6].The former is to synthesize the solid color dataset from the simplified information, without considering the shape of target object, while the latter is related to the solid texture and surface of the model. These methods are usually semi-automatic: the user needs to specify some properties of the object, and then the system will infer how to synthesize the internal texture. In addition, the color of each voxel that does not need to be directly stored for the internal model can implicitly be defines it in this method.

2.1. Liver Solid Texture Synthesis Method Selection

The data of liver texture synthetic method is collected from VHP (Visible Human Project) dataset, which is a set of continuous cross-section images of the normal human body and can solve the problems of a distance between adjacent layers through the interpolation. VHP dataset provides a good material for the solid texture synthesis. Because the cutting is the most common operation in a virtual surgery and the cutting face needs to be drawn, the solid texture can display a realistic face on the slicing table in any direction and is very suitable in the virtual surgery.

The solid texture synthesized by the boundary-independent method relies not on the model shape, but on a given dataset of the internal properties to construct the color dataset similar to the inputted color data in any section of the model. The solid texture synthetic method has a high reusability but is not suitable in the medical texture for different medical patients of different images, thus each constructed solid model and solid texture must be of personalized characteristics.

The solid texture synthesized by the boundary correlation method is subject to the constraints of the boundary surface, which is semi-automatically or manually analyzed and manually conducted. Because the solid texture has a high randomness, researchers must focus on how to handle the joints between the texture blocks and the constraint of boundary. In the medical application, the solid texture of liver model has to be personalized for different patients; thus, we have to synthesize the solid texture with more samples by the boundary correlation method.

2.2. Solid Texture Sample Set Processing

The liver solid texture must be synthesized on the basis of constructing the original images of the liver model, in which way the synthesized liver solid texture and liver model can properly fit and truly display the location and texture of the liver structure or lesions. In the construction of liver solid texture, we have to process the VHP dataset as the samples for the synthesized liver solid texture.

In the previous work of the subject, we have extracted the liver contour and saved the key fitting points of Bezier curve and the smoothing coefficient K in each fitting curve, and used the saved data to calculate the location of the control points.

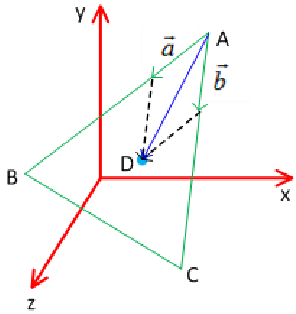


Figure 1. Patch Texture Generating Algorithm

If, use the key point B (x_1, y_1) and key point C(x_2, y_2) to generate the coordinates of two control points, set the key point A (x_n, y_n) as the point before the key point B, and the key point D(x_3,y_3) as the point after the key point C, thus, the lengths of line AB、BC and CD, *i.e.* l_{AB}、 l_{BC} and l_{CD} are respectively:

$$\begin{cases} x_{ctr1} = \left\{ \frac{x1+x2}{2} - \left[\frac{x0+x1}{2} + (\frac{x1+x2}{2} - \frac{x0+x1}{2}) \times r_1 \right] \right\} \times K1 + x1 \\ y_{ctr1} = \left\{ \frac{y1+y2}{2} - \left[\frac{y0+y1}{2} + (\frac{y1+y2}{2} - \frac{y0+y1}{2}) \times r_1 \right] \right\} \times K1 + y1 \\ x_{ctr2} = \left\{ \frac{x2+x3}{2} - \left[\frac{x1+x2}{2} + (\frac{x2+x3}{2} - \frac{x1+x2}{2}) \times r_2 \right] \right\} \times K2 + x2 \\ y_{ctr2} = \left\{ \frac{y2+y3}{2} - \left[\frac{y1+y2}{2} + (\frac{y2+y3}{2} - \frac{y1+y2}{2}) \times r_2 \right] \right\} \times K2 + y2 \end{cases} \tag{1}$$

Then, the proportion r_1 of the length of AB in the total length of AB and BC, and the proportion r_2 of the length of BC in the total length of BC and CD, are respectively:

$$\begin{cases} l_{AB} = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2} \\ l_{BC} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \\ l_{CD} = \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2} \end{cases} \tag{2}$$

Calculate the values of r_1 and r_2 for setting two points in median lines of line AB and BC, line BC and CD, then, remove the two points in parallel to the location of key points B and C, then multiplied by the corresponding smoothing factor $K1$ and $K2$, and finally obtain the coordinates of two control points $ctr1$ and $ctr2$.

$$\begin{cases} r_1 = l_{AB} / (l_{AB} + l_{BC}) \\ r_2 = l_{BC} / (l_{BC} + l_{CD}) \end{cases} \tag{3}$$

Calculate the coordinates of two control points $ctr1$ and $ctr2$, then run the Bezier curve formula three times to reconstruct the liver contour information of each image.

Because only the color in the liver region of the image is useful in the synthesis of the liver solid texture, we have to re-cut the VHP dataset based on the contour of each image, and fit white color in the outside of the liver region. Select the square as the cutting shape to cover the liver region of each image so as to minimize the data of the solid texture and become easily compressed.

By connecting each liver contour point, cut a square with a side length of 546 pixels to have each cutting area contain the liver region of each image. According to the contour, fill the non-liver region with white color, and the processed image is shown as Figure 2:

(a) Image No.22 (b) image No. 67 (c) image No. 148

Figure 2. Solid Texture Image after Color Fit

2.3. Solid Texture Synthesis

The layer space between axial dissection images of VHP dataset is 1mm, and the space between image pixels is 0.33mm. In order to get a synthetic solid texture with equal distance (or resolution) in length, width and height, two layers must be inserted between adjacent layers. The shape-based interpolation method could interpolate the contours in between the adjacent layers to construct a liver model, and the process is described as follows:

Set two adjacent layer images as the K-1 layer and the K+1 layer and the spacing of 1mm between two images, the pixel value of 0.33mm, and the ultimate objection is to interpolate the pixel (i,j) in K layer based on the two images. The (i,j) pixel and its surrounding pixels is as shown in Figure 3.

(i-1,j-1)	(i,j-1)	(i+1,j-1)
(i-1,j)	(i,j)	(i+1,j)
(i-1,j+1)	(i,j+1)	(i+1,j+1)

Figure 3. (i,j) Pixel and Surrounding Pixels

The (i,j) pixel in K layer can be presented by the (i,j) pixel of K-1 layer and the (i,j) pixel of K+1 layer as well as their surrounding pixel values. The (i,j) pixel value is more related to its adjacent upper and lower pixel values, and less related to the surrounding pixel values. Each pixel can be set with a different weight to represent the mean value of (i,j) pixel, $\bar{v}_{k(i,j)}$ representing the average pixel value of (i,j) pixel in K layer, then.

$$\begin{cases} \bar{v}_{(k-1)(i,j)} = r\left(v_{(k-1)(i-1,j-1)} + v_{(k-1)(i,j-1)}\right) + v_{(k-1)(i+1,j-1)} + v_{(k-1)(i-1,j)} + v_{(k-1)(i+1,j)} + \\ v_{(k-1)(i-1,j+1)} + v_{(k-1)(i,j+1)} + v_{(k-1)(i+1,j+1)} + \left(1-8r\right)v_{(k-1)(i,j)} \\ \bar{v}_{(k+1)(i,j)} = r\left(v_{(k+1)(i-1,j-1)} + v_{(k+1)(i,j-1)}\right) + v_{(k+1)(i+1,j-1)} + v_{(k+1)(i-1,j)} + v_{(k+1)(i+1,j)} + \\ v_{(k+1)(i-1,j+1)} + v_{(k+1)(i,j+1)} + v_{(k+1)(i+1,j+1)} + \left(1-8r\right)v_{(k+1)(i,j)} \end{cases} \tag{4}$$

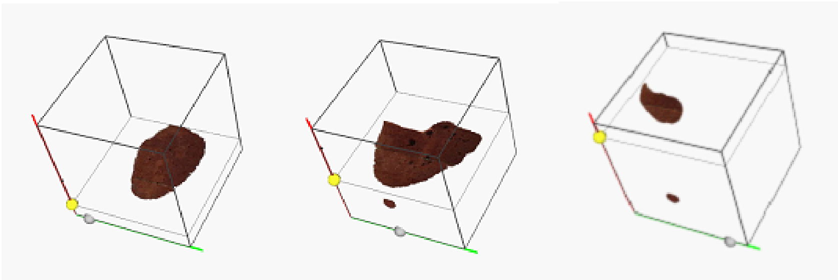
Where, r is weighting factor of (i,j) pixel 8 connecting the neighboring region, $0 \le r \le 1/8$. Assuming the coordinates of K-1， K， K+1 layers in Z direction are respectively Z_{k-1},Z_k and Z_{k+1}, and the interpolated pixel value of K layer is $V_{k(i,j)}$:

$$v_{k(i,j)} = \frac{Z_{k+1} - Z_k}{Z_{k+1} - Z_{k-1}} \cdot \bar{v}_{(k-1)(i,j)} + \frac{Z_k - Z_{k-1}}{Z_{k+1} - Z_{k-1}} \cdot \bar{v}_{(k+1)(i,j)} \tag{5}$$

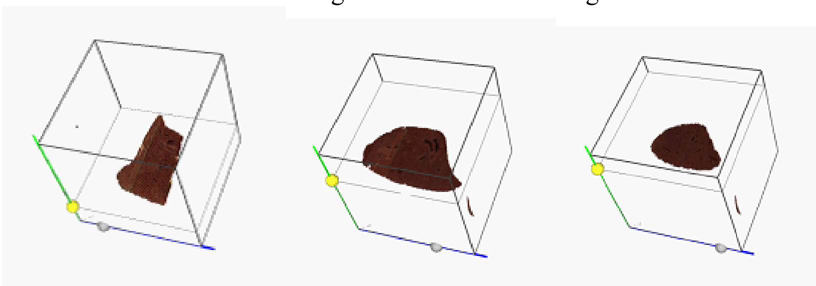
The texture sample is only left with the liver region after processed, and the other regions are filled with white color. In the interpolation between layers, the upper and lower images are first scanned, and only the pixel including the liver region can be calculated. The above algorithm is, however, not suitable in the interpolation of liver edge pixel because the region connecting pixel 8 contains the white region. We can use the pixels of $k-1$ layer and $k+1$ layer for interpolation:

$$v_{k(i,j)} = \frac{Z_{k+1} - Z_k}{Z_{k+1} - Z_{k-1}} \cdot v_{(k-1)(i,j)} + \frac{Z_k - Z_{k-1}}{Z_{k+1} - Z_{k-1}} \cdot v_{(k+1)(i,j)} \tag{6}$$

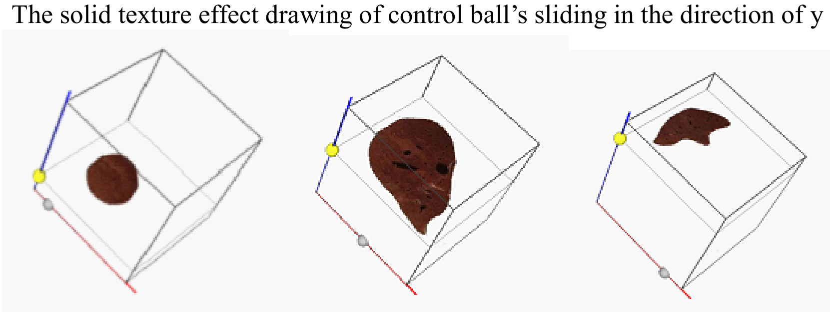
The original images are 177, if two images are inserted in adjacent layers to create 352 new images, a total of 529 images can be achieved. Based on the number of the texture sample, obtain the color information in sequence, then use the location of the color information to obtain the synthetic liver texture, as shown in Figure 4.



The solid texture effect drawing of control ball's sliding in the direction of x



The solid texture effect drawing of control ball's sliding in the direction of y



The solid texture effect drawing of control ball's sliding in the direction of z

Figure 4. The Texture Effect Figure in the Direction of Axis Direction

3. Liver Solid Texture Mapping

The above solid texture synthetic methods have established the liver solid model and synthesized the liver solid texture, then the liver solid texture must be mapped onto the liver solid model. Because the liver solid model is rendered by the liver surface rendering method to synthesize the liver solid texture, the surface of the liver model needs to be inserted into the space of the liver solid texture, and to obtain the surface liver texture. There are two basic problems: solid texture space expansion and solid texture atlas generation.

3.1. Liver Solid Texture Space Expansion

If the liver model surface is inserted into the space of the liver solid texture, the size of the liver model cannot be larger than that of the liver solid texture. In this paper, the establishment of the liver model and the synthesis of liver solid texture are directly derived from VHP image sets, using the same liver contour to establish the liver model or extract the texture information. If the layer interpolation values between adjacent layers are the same, the liver model be completely inserted into the liver solid texture. In fact, in order to provide surgeons with the diagnosis information, the liver solid texture cannot be expanded randomly, because the relationship between the liver model and the solid texture must be maintained to reflect the liver texture, so as to provide surgeons with the diagnosis information. In the process of the algorithm, we have to normalize the liver model and the liver solid texture.

3.2. Liver Solid Atlas Generation

In order to improve the efficiency of graphics hardware to conduct the real-time rendering of the complex scenes, storing the mapping textures into the texture atlas is the common method [9]. A texture atlas is a collection of many textures, which is essentially a main texture containing many sub textures. The sub texture in the texture atlas stores a local texture on the surface of the object, that is, the texture atlas contains all the textures to be mapped into the texture of the solid model. In the process of the texture mapping, only a simple transformation can search the corresponding texture in the texture atlas.

Both the surface triangle patch and the location of each triangle patch vertex in any case can be obtained. After the normalization of the liver model and liver solid texture, the coordinates of surface triangle vertex of the liver model is marked by the location of the color in the solid texture coordinates. The solid texture of the triangle patch can be constructed based on the locations of three surface triangle vertexes of the solid model. If the coordinates of three vertexes are respectively $A(x_0, y_0, z_0)$, $B(x_1, y_1, z_1)$ and $C(x_2, y_2, z_2)$, any vertex D(x, y, z) in the triangle region can be obtained, as shown in Figure 1.

All the texture values of points in the region shall be determined by three vertexes of the triangle. Two non-collinear vectors can be used to present the nature of any point determined by two vectors in the plane, hence find any D(x, y, z) in the region of triangle ABC, which can be illustrated as follows:

$$AD = \alpha AB + \beta AC \tag{7}$$

Where, $0 \le \alpha \le 1, 0 \le \beta \le 1$ and $\alpha + \beta \le 1$,if $\alpha = 0, \beta = 0$,point A; if $\alpha = 1, \beta = 0$, point B; if $\alpha = 0, \beta = 1$, point C. Use the formula (8):

$$\begin{cases} (x - x_0) = \alpha(x_1 - x_0) + \beta(x_2 - x_0) \\ (y - y_0) = \alpha(y_1 - y_0) + \beta(y_2 - y_0) \\ (z - z_0) = \alpha(z_1 - z_0) + \beta(z_2 - z_0) \end{cases} \tag{8}$$

All the points in the triangle region can be found by calculating the values of α, β . Set the step value of α, β as an half of the reciprocal of the total length of AB and AC, that is, set the lengths of AC and AB respectively as l_{AB}, l_{AC} (unit: pixel), thus the step values of α, β are respectively $\frac{1}{2l_{AB}}, \frac{1}{2l_{AC}}$, Calculate the coordinates of D(x, y, z), round the numerical values to integral numbers, thus obtain a better experimental result. The liver solid texture mapping effect and the corresponding texture atlas are shown in Figure 5:

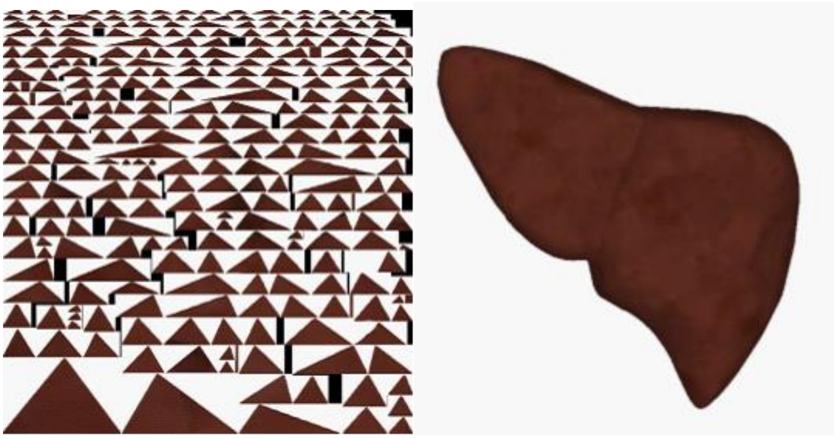


Figure 5. Solid Texture Atlas and Mapping Model

4. Results and Analysis

The configuration of the PC in which the experimental prototype system is developed is specified as follows: CPU: Intel® Core™ i5-2300 CPU @2.80GHz;memory (RAM): 4.00GB (3.61GB available); display card: NVIDIA GEFORCE GT 430(512 MB); main board: Intel DH67BL (Intel Sandy Bridge); hard disk: Seagate 1T(7200 RPM); operating system: Windows 7 flagship edition Service Pack 1 (32 bit); integrated development environment (IDE): Microsoft Visual Studio Ultimate 2012;. NET Framework version number: 4.5.50709; OpenCV version number: 2.3.0; OpenGL version number: 4.1.0.

Extract the liver contour and save the results. The saved data is the key point of Bezier curve fitting and the smoothing parameter K of each section of curve fitting; reload the data and use the Bezier curve to obtain the contour of each image. According to the liver contour information, clip and fill each image, so as to effectively remove the non-liver region and minimize the texture data size of the liver solid texture.

Liver model is made by surface rendering method. If the synthesized liver solid texture is mapped onto the surface of the liver model, the surface of the liver model needs to be inserted into the space of the liver solid texture to extract the surface texture. In order to improve the efficiency of the graphics hardware to conduct the real-time rendering of the complex scenes, a rotating triangle is used so that the longest side is in the horizontal direction to construct the triangular bounding box, which is then filled with the texture atlas in the decreasing sequence of the height to generate the texture atlas. The liver solid texture constructed after the synthesis of the texture atlas is shown in Figure 6.

Figure 6. The Effect Drawing of Liver Solid Texture

This study, which focuses on the research direction of the virtual operation system, is developed from the view of improving the reality of the rendering system and the vision telepresence of the operators. We process and use the VHP images to construct the liver solid texture and visualize the liver solid texture. Meanwhile, we map the synthesized liver solid texture onto the liver model, and use the texture atlas to realize a fast rendering. This paper tends to improve the performance of the virtual surgery system by enhancing the vision telepresence, so as to provide some reference for further studies of the virtual surgery.

Aiming at the realistic problems in virtual surgery system, the progress has been made in the establishment of the model construction and the synthesis and mapping of the solid texture.

There are still some challenging issues left. In the synthesis of solid texture, the texture data are very large while the process is very slow; in addition, the compression algorithm of solid texture has to be further improved. The synthesis of solid texture is an important subject for further studies.

In the mapping of solid texture, the real-time performance of the surgery system decreases with the increase of the complexity of liver model. Therefore, how to improve the real-time performance of the system turns out to be an urgent problem in the virtual operation system.

The deformation of the liver model under the external forces is also an important issue to be considered in the further study.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (31100415) and the Technology Projects of Fujian Province Education Department (JA10038, JA09005).

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