

3D Reconstruction Method of Leather Fiber Bundle Weaving Network

by

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Abstract

A 3D reconstruction method of leather fiber bundles and their weaving network was developed. The main steps included: leather metallographic sample preparation, sequential section images acquisition, registration and alignment, image preprocessing and 3D reconstruction. Metallographic sample preparation and layer-by-layer grinding methods were used to obtain sequential sections images. 3D-Doctor medical reconstruction software was used to implement the 3D reconstruction of leather fiber bundles. Features and cautions of each step were discussed, and some reconstruction results were displayed.

Introduction

The main architecture of leather is 3D net structure formed through tightly braiding of collagen fiber bundles. 3D weaving network of collagen fiber bundles is the structural basis of physical and mechanical properties of leather, recognition and study of which from 3D spatial angle will effectively promote the study of relationship between leather structure-properties and contribute to improvement and development of leather manufacturing technology as well as production of high-performance leathers with different uses.¹

Leather 3D weaving network can be obtained through 3D reconstruction technology. After multiple 2D images of the objects acquired by certain means are input in the computer, 3D reconstruction technology reconstructs 3D stereo structure of the target object based on 2D geometric information and topologic information of related objects obtained through computer processing.^{2,3} Through nearly continuous hundred-year development, this technology has been extensively applied in various research fields,⁴⁻⁸ where the most mature application is in medical aspects, in which nearly all human organs and systems are reconstructed. Moreover, some specialized

reconstruction software has been successfully developed like 3D-Doctor, V-works, VG-Studio, Voxblast, MimicS and 3D-Med. The basic steps include: acquisition of sequential section images, image processing, 3D reconstruction and visualization.⁹

With the scientific development in recent years, 3D reconstruction technology has been listed in leather field. E. Bittrich *et al.* used μ CT to acquire sequential section images in 2014, reconstructed some fiber bundles using artificial image segmentation method and changed traditional study method of leather structure,¹⁰ but their method was not suitable for chrome tanning leather, and moreover, the image segmentation mainly relied on artificial method with low efficiency. In short, as leather fiber bundles are small and thin with complicated braiding structure, there are few studies on this aspect without a set of systematic and highly efficient 3D reconstruction method of leather fiber bundles network.

After many experiments, a new 3D reconstruction method of leather fiber bundles network was explored based on early-stage study on metallographic leather sample preparation method.^{11,12} This method was introduced and discussed in detail in this paper.

The main objective of this work was: (1) to establish an accurate and feasible method for obtaining sequential leather cross-section images for 3D reconstruction; (2) to explore suitable image processing methods to align sequential images and extract leather fiber boundaries; (3) using 3D-doctor software to reconstruct leather fiber bundles.

Materials and Methods

Experimental Materials and Instruments

Dried pieces of blue stock of chrome-tanned cattle hide was chosen for this work. The embedding medium was epoxy resin. The grade of epoxy and its hardener were E-51 and 593#,

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respectively, purchased from Jinan TianMao Resin Company, China. The mass ratio of epoxy/hardener was 4/1. The optical images of samples were recorded on ZEISS Smartzoom5 optical microscope, German (diagonal line of 17.5 inches display and 4:3 screen ratio was used as reference standard of the amplification factor, and the following amplification factors were all based on this standard). The leather sections were obtained by the OUBEITE MP-2000 grinding and polishing machine, China.

Experimental Procedure

The main steps were shown in Figure 1. In Figure 1, a-d showed metallographic sample preparation steps, and e-h showed the sequence images acquisition by layer-by-layer grinding methods. 3D reconstruction was implemented using 3D-Doctor software after image processing, and concrete steps were as follows:

Metallographic Sample Preparation of Leather

Tailored dry leather sample (about 20 mm × 4 mm × 2 mm) was soaked in epoxy resin and cured into solid small sample strips, the observational section was polished out and inlaid into central position of epoxy resin 40 mm in diameter and 20 mm in height, and then metallographic leather sample (Figure 1) was prepared after grinding and polishing¹². For the convenience of registration, two parallel metal wires perpendicular to observational section could be pre-embedded in the position clinging to the sample as registration markers.

Acquisition of Sequential Section Images

Step 1. The set thickness of metallographic leather sample was away using 3,000-mesh waterproof abrasive paper in the direction perpendicular to observational section on polishing

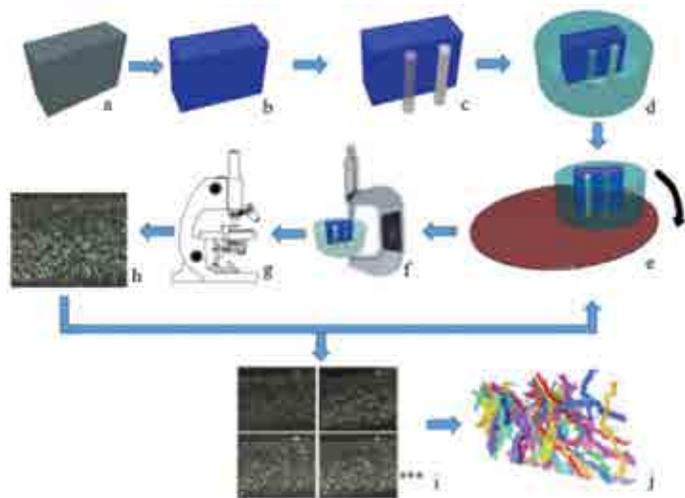


Figure 1. Diagram of 3D reconstruction steps of leather fiber bundles (a-leather, b-cured leather impregnated with resin, c-two metal wires were attached, d- metallographic leather sample, e-grinding and polishing, f-thickness measure, g- section image acquired on microscope, h-section image, i-sequential section images, j-3D reconstruction leather fiber bundles.)

machine. Then the new section was polished using a napped cloth on the polishing machine.

Step 2. Thicknesses of the metallographic leather sample at four points (near the leather sample, distributed evenly) were measured using micrometer caliper and recorded.

Step 3. The section image of this layer was acquired on microscope, namely one of the sequential section images.

Step 4. Step 1-3 were repeated to acquire a series section images successively so as to finally acquire sequential section images.

Step 5. Thickness differences at the four points in the two computing processes were respectively computed, mean value of the four was taken as the spacing distance between two adjacent sections (images) so as to obtain interlayer spacing between sequential section images.

Figure 2 was the acquired continuous 4 sequential section images and its interlayer spacing was $15 \pm 1 \mu\text{m}$.

Registration and Alignment of Sequential Section Images

As sample position had slight deviation during each image acquisition process, the acquired sequential section images should be registered and aligned. The image to be registered was masked on the reference image after semi-transparentizing treatment, and several section feature images of fiber bundles or feature points were selected as prior reference points. Image position to be registered was manually regulated so that it overlapped with the reference image (at prior reference points), and then the image in new position was saved.

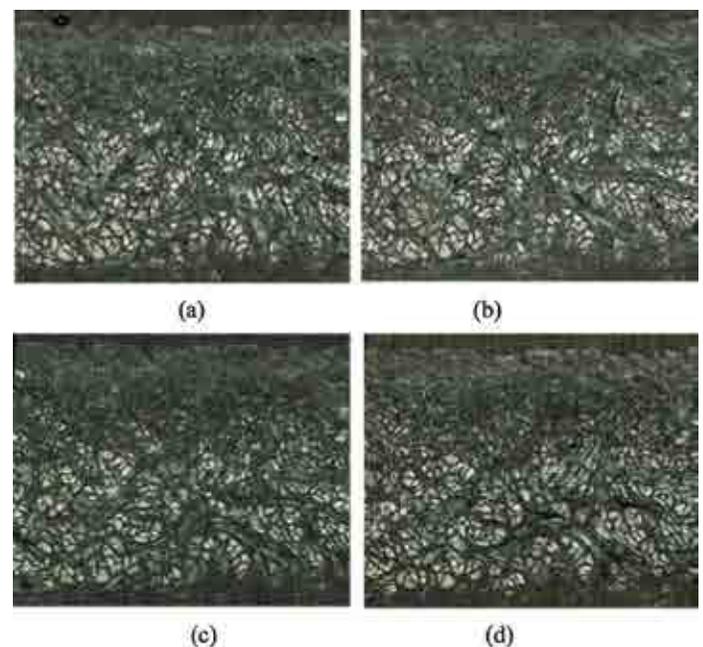


Figure 2. Four sequential section images of leather (400×)

For sequential section images with pre-embedded mark points, registration could be completed as long as two (or more) mark points were aligned, and this could be decomposed into translation and rotation operations. As shown in Figure 3, image (a) is reference image, image (b) is image to be registered, and there are circular cross sections (bright spots) of two pre-buried metal wires in the middle of the image. During registration process, the image to be registered was masked on the reference image, it was set as semi-transparent, the reference image could be seen through the image to be registered, as shown in Figure 3 (d). Moved the image to be registered to make the two bright spots at left were overlapped (Figure 3e), then rotated the image to be registered, to make both bright spots were aligned with the reference point (Figure 3f), and the image in new position was saved as the image after registration (Figure 3c).

When sequential section images were registered, the first image was generally selected as reference image, then the second image would be registered, after which it was taken as reference image to register the third one, and then the third one was used as reference image to register the fourth one...until all sequential

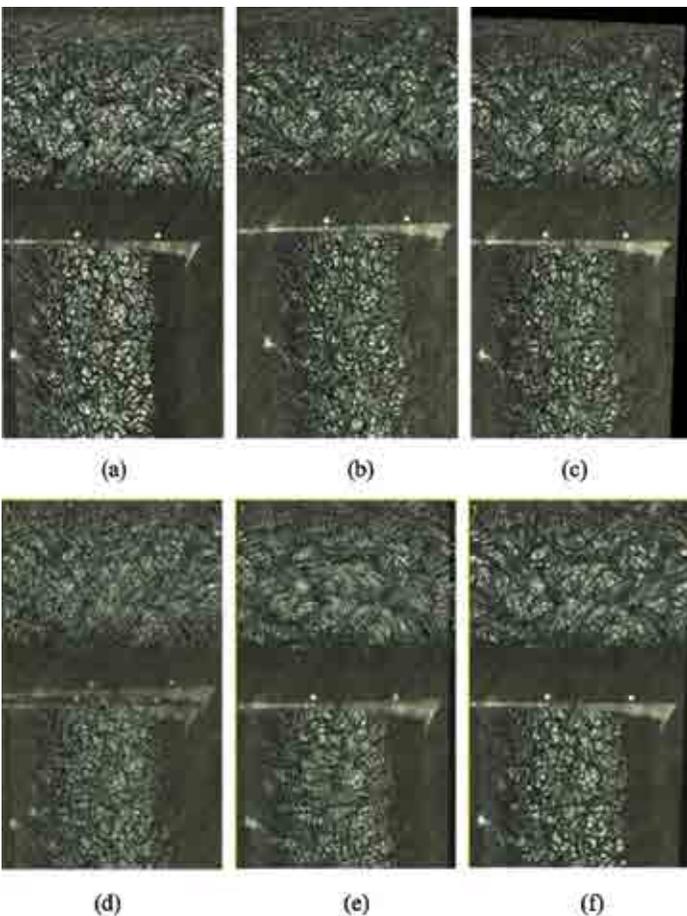


Figure 3. Registration and alignment of two section images (a-reference image, b-image to be registered, c-image after registration, d-image b was masked on image a, e-image b was moved, f-image b was rotated.)

section images were registered. Or one image in the middle could be firstly selected as reference image, and registration would be implemented towards images before and after the selected image successively.

Image Preprocessing

Noises like small scratches and speckles unavoidably existed on acquired sequential section images of the leather section. In order to reduce noises, enhance image features and elevate signal to noise ratio, median filtering and despeckling processing should be carried out for the images by image processing software (Figure 4b). For better extraction of image boundaries on fiber section, binarization processing should be implemented for the images (Figure 4c).

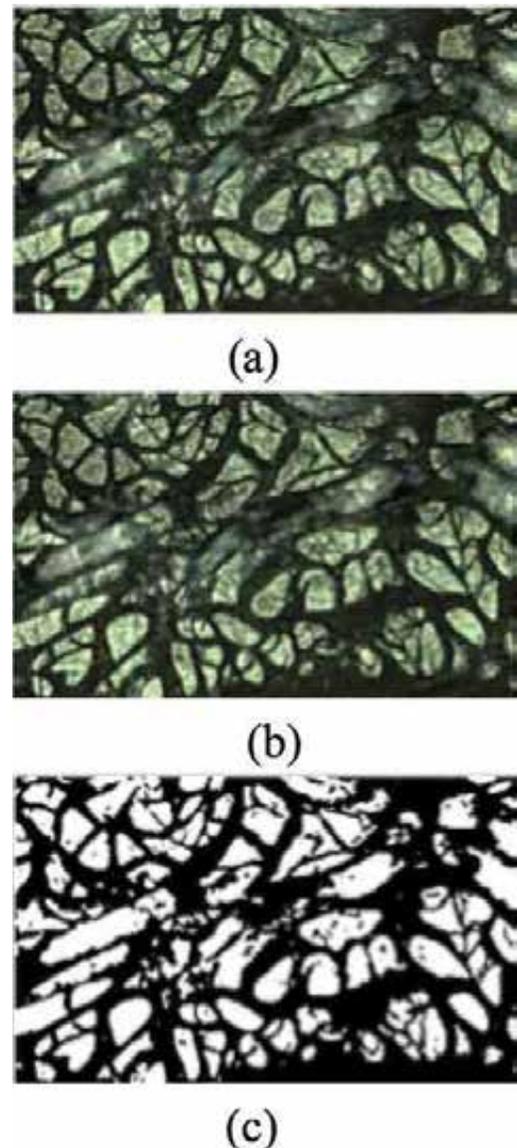


Figure 4. Image processing (a-original image, b- median filtering and despeckling, c- binarization image).

3D Reconstruction Using 3D-Doctor Software

3D reconstruction of leather reticular layers was carried out using 3D-Doctor software as shown in Figure 5. Basic steps were as follows:

Step 1. A New Stack was built, and continuous sequential section images after processing were imported.

Step 2. Pixels of sequential section images in directions of X axis and Y axis as well as Z axis (interlayer spacing) were input in Calibration term.

Step 3. Region of interest was selected.

Step 4. Boundary extraction. This software provided multiple boundary extraction modes, including full automatic segmentation extraction, extraction according to threshold setting, semi-automatic extraction by dividing small regions, artificial delineation, etc. Boundary extraction mode could be flexibly selected according to image status so as to extract boundary of each fiber bundle. Threshold value method could be used for the images after binarization processing. All boundaries were exported and saved as boundary file (Figure 6a,b).

Step 5. Boundary file was imported onto sequential section images not going through image pre-processing for verification and adjustment (Figure 6c). For example, if cross-sectional area of fiber bundle parallel to observational surface was large and complicated, boundaries automatically extracted had poor accuracy, and adjustment or auxiliary artificial description was needed.

Step 6. Naming of fiber bundle boundaries. Leather had numerous fiber bundles. For the convenience of differentiation and reconstruction, it's necessary to name sections on different section images of each fiber bundle, and sections belonging to the same fiber bundle had the same names. For one fiber bundle, an object was built in Set Object, naming and color setting were implemented (colors of neighboring fiber bundles should be

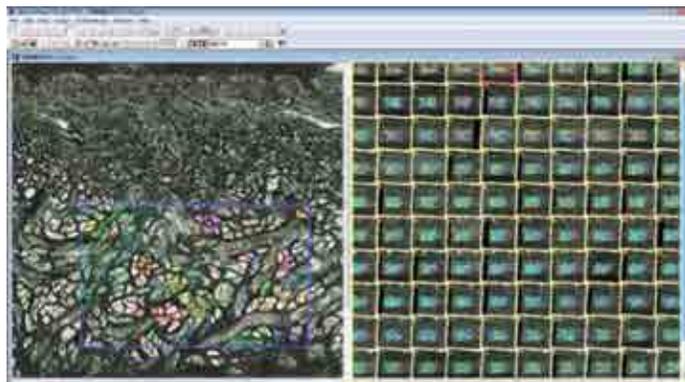
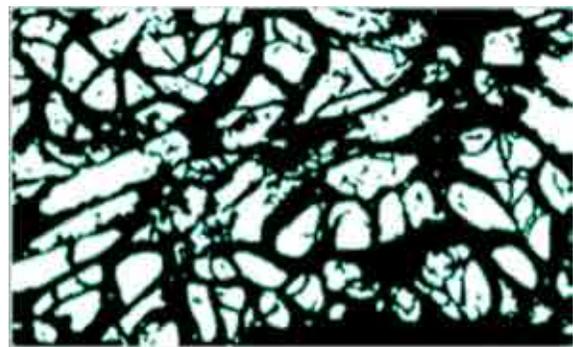
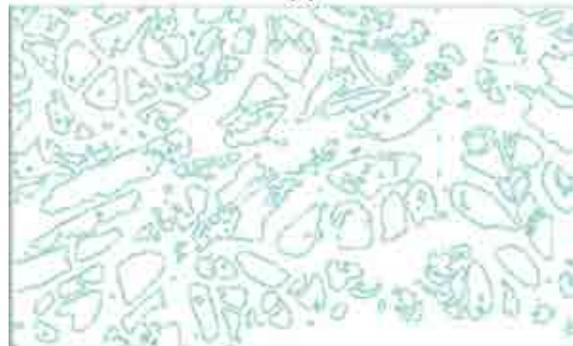


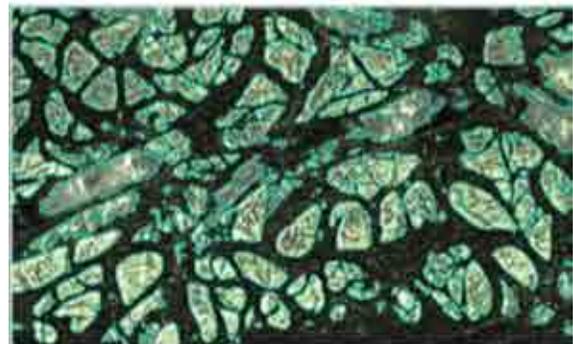
Figure 5. Interface of 3D-Doctor software.



(a)



(b)



(c)



(d)

Figure 6. Boundary extraction and processing boundary extraction from binarization image, b- fiber bundle boundaries, c- boundaries was imported onto the original image, d- named boundaries after adjustment).

different), then all sections belonging to this fiber bundle in sequential section images were belonged to this object, and a new boundary file was generated after all fiber bundles were respectively named and belonged (Figure 6d).

Step 7. 3D reconstruction. 3D stereo model was reconstructed and displayed through Surface Rendering and Volume Rendering.

Step 8. Saving and observational study of stereo model. Reconstructed model could be observed and calculated from different angles in any plane and its parameters could be measured. Parameters of fiber bundle like diameter, perimeter, superficial area, volume, length and angle could be measured and calculated.

Results and Discussion

Basic 3D reconstruction steps of leather fiber bundle weaving network included: metallographic leather sample preparation, acquisition of sequential section images, registration, image processing, 3D reconstruction and visualization, and the following conclusions were drawn through the test:

Effect of Metallographic Leather Sample Preparation

After resin soaking and curing treatments, leather fiber bundles were solidly fixed in leather-resin composite material so that they would not fall off or deform during follow-up grinding and polishing process, which guaranteed accuracy of 3D reconstruction result; under bonding effect of resin, small fibers in fiber bundles truly gathered together to form resin-fiber phase, and resin phase was formed after the gap between fiber bundles was filled with resin. Difference between resin-fiber phase and resin phase in reflection degree to light was great due to their differences in physical properties, which resulted in large contrast ratio of fiber bundle and gap in section images. As a result, sectional boundaries of leather fiber bundles became clear, which was helpful for follow-up image processing and automatic boundary extraction.

Cautions in Acquisition of Sequential Section Images

Acquired sequential sections were made mutually parallel. Positions of sample holder and sample were adjusted to ensure that the sample was perpendicular to grinding/ polishing table each time.

The four measured points each time were guaranteed at the same corresponding position point. Back face (not polished face) of metallographic leather sample could be marked, and the same position point was measured each time.

Thickness ground away each time should be the set thickness. In order to prevent the thickness grinded away being too large which would result in missing section and then failure, low rotation speed (90 rotations/min) and “small quantity and many rotations” method could be used. In other words, the measurement would be implemented once after grinding for about 10sec. Continuous grinding time and measurement times could be determined according to thickness ground away and thickness to be grinded away.

When the thickness was greater than the set thickness for about 1 micrometer, grinding could be stopped, and the thickness could be removed through thinning effect of polishing.

Image Registration Skills

During image registration without markers, 2-3 section images of fiber bundles perpendicular to the observation surface could be selected as feature images, because fiber bundles perpendicular to the observational section would go through minor change in shape and direction within 10 micrometers range, namely shapes and positions of the perpendicular fiber bundle sections adjacent to selected images basically didn't change, both could be aligned very well, and their image brightness was high with easy identification.

Section feature images of fiber bundles would frequently change, they should better be changed every other 2-3 images, and one feature image should not be used to the end. Because when interval was large, directions of fiber bundles might change. If they were aligned again, it would cause error.

Selection of Image Processing Method

The objective of image processing was accurate extraction of fiber bundle boundaries, so protection of section image boundaries of fiber bundles should be firstly taken into consideration. Elimination of noises like scratches and speckles should not damage fiber bundle boundaries. Therefore, median filtering was selected for noise reduction. Value of each pixel point is replaced by median of grey levels of all pixel points inside neighboring window around the point so as to eliminate isolated noise points in this method. As a nonlinear lowpass filtering technology, this method is usually applied to image processing for edge protection and it's a classical method for noise smoothing. Similarly, in binarization processing process through threshold regulation, threshold should be determined according to the principle of protecting fiber bundles from being damaged.

3D Reconstruction of Leather Fiber Network Using 3D-Doctor Software

As a medical 3D reconstruction software developed by American Able Corporation, 3D-Doctor software has many functions like automatic or interactive image segmentation, surface rendering,

volume rendering, 3D image processing, measurement, etc. With abilities in boundary extraction of target image, 3D reconstruction and visualization, it has been extensively applied to 3D reconstruction of human organs and so on. However, leather fibers are criss-cross and have large difference from medical reconstruction targets. Therefore, functional selection, improvement and application of 3D-Doctor software should be implemented according to features of leather fiber bundles:

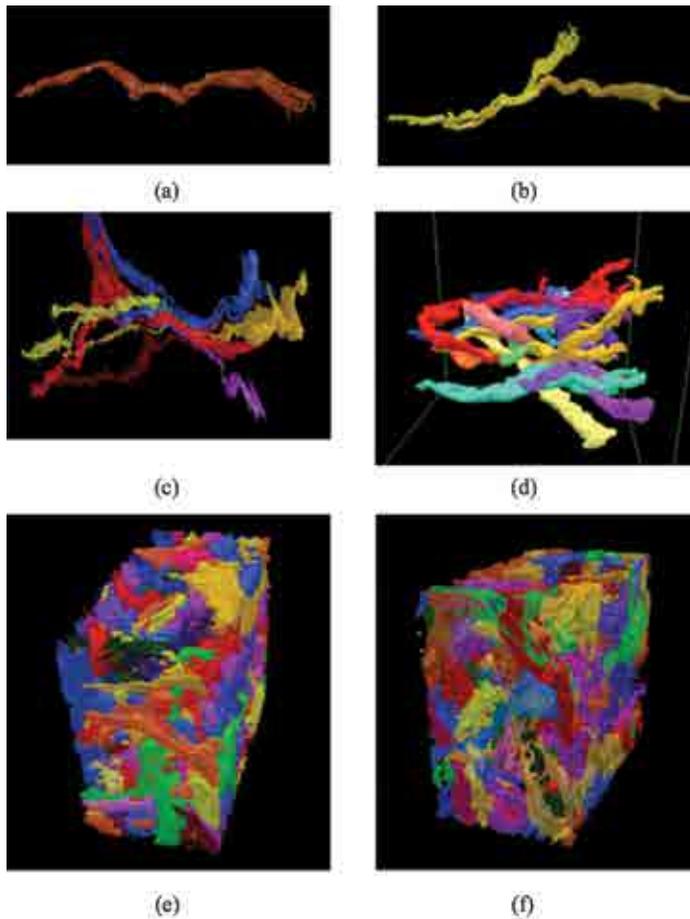


Figure 7. 3D reconstruction results by surface rendering (400×) (a, b, c- leather fiber bundle with different form, d-a lot of leather fiber bundles, e, f-partial leather reticular layer with different perspective).

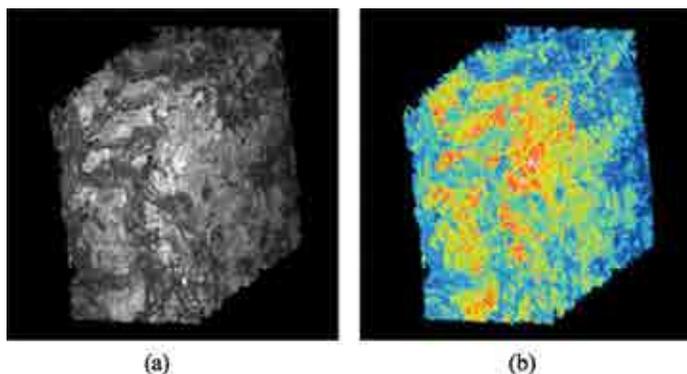


Figure 8. 3D reconstruction of leather reticular layer by volume rendering (400×) (a-grayscale pattern, b-color pattern).

Binarization processing of sequential section images was implemented in advance, which was convenient for boundary extraction using 3D-Doctor software. After boundary extraction, the boundary would be put into original sequential section images for correction and processing so as to improve boundary extraction accuracy of intricate leather fiber bundles.

All fiber bundle boundaries were numbered and named, and the same serial numbers were assigned to section images (boundaries) belonging to the same fiber bundle (including splitting or integrating), which was good for separate display of fiber bundles and parameter extraction.

There were differences between surface rendering and volume rendering. Surface rendering, also called indirect rendering, is an abbreviation of surface-based 3D rendering method. It's a method of describing 3D structure of the object after geometric units (triangles) are spliced into surface of fitted object. Based on boundary (or profile) extraction of 2D target image, it is implemented with the help of traditional image processing technology. Volume rendering, also called direct rendering, is abbreviation of volume data-based 3D rendering method. It generates 3D images through re-sampling and synthesis of volume data directly according to applied visual principles. As internal compositions of leather fiber bundles are single and uniform, surface rendering results in 3D-Doctor software are of strong sense of reality. Different colors can be assigned to different target fiber bundles so that the reconstructed body can be observed and analyzed from multiple angles and levels (Figure 7). Internal structures of fiber bundles in volume rendering results are more real, but as voxels don't have color properties only with grey level difference, color difference between different fiber bundles is not great, so it's difficult to differentiate (Figure 8a). Even though certain color change happens according to change of grey level, differentiation of fiber bundles is not that obvious (Figure 8b). Therefore, surface rendering is mostly used in morphological study of fiber bundles. Volume rendering is used only when it's combined with finite element analysis.

Morphological Analysis of Fiber Bundles

The software has functions of measurement and quantitative analysis of 3D images, and it can simply and rapidly measure length, superficial area, volume, bending angle and so on of the target fiber bundles. Through statistical processing of these data, weaving angle, porosity and pore size can be computed so as to explore into leather weaving laws, pore connection status, etc. And our study in this aspect is underway.

Conclusions

In this article, 3D reconstruction method and reconstruction steps of leather fiber bundles and their weaving network were introduced in detail. Firstly, section images for 3D reconstruction was established. Metallographic sample preparation and layer-by-layer grinding methods were used to obtain sequential sections images. interlayer spacing between sequential section images was measured by micrometer caliper. Then, suitable image processing methods was explored to align sequential images and extract leather fiber boundaries. Finally, 3D-doctor software with improved steps was used to reconstruct leather fiber bundles.

By virtue of simple operation, low cost and high accuracy, this method will make a significant contribution to obtain 3D morphologies of all kinds of fiber bundles and stereo structure of leather fiber bundle braiding.

Acknowledgements

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