3D IMAGE BASED STRUCTURAL ANALYSIS OF LEATHER FOR MACROSCOPIC STRUCTURE-PROPERTY SIMULATION

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Abstract. The intrinsic structure significantly influences the mechanical properties of leather. Deeper insight into the leather's hierarchical structure is therefore essential for optimising choice and processing of the leather for the intended application. 3D imaging, quantitative image analysis combined with stochastic micro-structure modelling and numerical simulation of macroscopic properties is a promising approach to gain a deeper understanding of the complex relations between the leather's micro-structure geometry and its material properties. For leather, both imaging and image analysis are particularly challenging, due to the multi-scale nature of the leather's micro-structure. Segmentation of typical structural elements at varying scales has been achieved by sophisticated morphological image processing based on local orientations. This approach lacks, however, of robustness. Here, recent results for morphology on the space of directions in 3D are used to improve the segmentation method.

1 Introduction

Leather material is well established for applications in upholstery and automotive interiors. Knowledge regarding leather properties is as old as humankind as the material is highly variable, not the least due to structural variations depending on species, race, gender, age, husbandry conditions as well as individual body parts and tanning processes. However, quantification e.g. of the impact of the collagen-based leather structure's anisotropy on the leather's physical properties is both, of great interest and still challenging.

The mechanical properties of leather are significantly influenced by leather's intrinsic structure. In consequence, knowledge of the leather's hierarchical structure is essential in order to find the most suited leather for a specific application. Leather structure based parameters are of major importance for both manufacturing and leather processing industries. Therefore, the leather structure has been investigated intensively in continuous research work. 2D microscopic studies of the structure of leather revealed significant structural differences. The 3D microstructure of leather has been studied, however, only recently. Non-destructive testing methods like ultrasound imaging, small angle X-ray scattering, and computed tomography (CT) have been applied to capture structural features of the collagen fiber bundles.

Quantitative image analysis combined with stochastic micro-structure modelling and numerical simulation of macroscopic properties is a promising approach to gain a deeper understanding of the complex relations between a material's micro-structure geometry and its macroscopic properties. A key ingredient for this is a reliable geometric description provided by the quantitative analysis of 3D images of the materials micro-structures. For leather, both imaging and image analysis are particularly challenging, due to the multi-scale nature of the leather's micro-structure (**Fig. 1**).

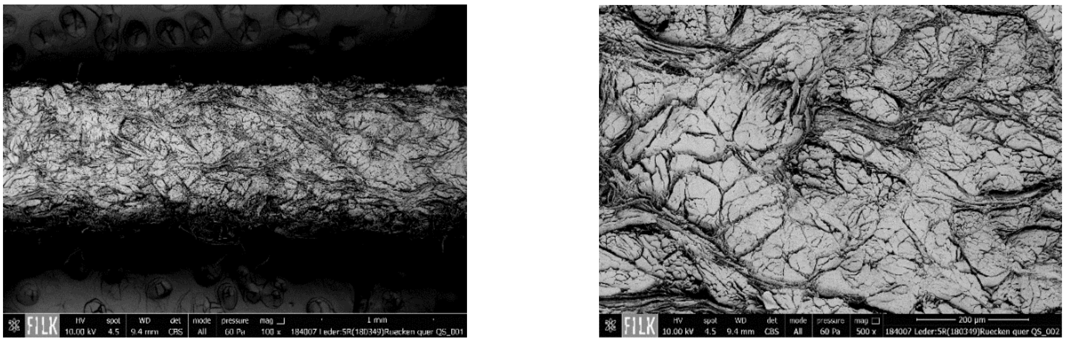

Fig. 1. Exemplary SEM images of bovine split leather sample revealing the bundle as well as fibre and fibril sub-structure morphology.

Moreover, opposite to man-made multi-scale materials, the scales in the leather are not well separated. Previous work [1, 2] showed that high resolution computed tomography allows 3D imaging of purely vegetable tanned leather samples at micro- and sub-micro-scale and (**Fig. 2**).

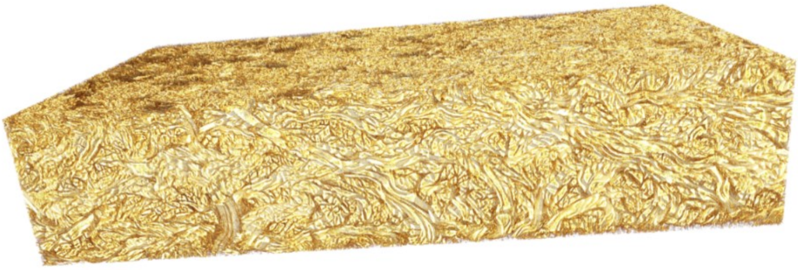

Fig. 2. Volume rendering of a reconstructed micro-computed tomography image of a vegetable tanned leather sample shown in Fig. 1; Voxel edge length 3.3 µm, 1 646 x 823 x 356 voxels.

Predicting the leather's mechanical properties based on the observed micro-structure calls, however, for a suitable representation of the latter. That is, first the solid leather has to be separated from the pore space. Subsequently, the solid structure has to be divided into typical structural elements, simplifying the local structure while keeping the essential connectivity and inclusion information. Both these tasks are segmentation issues. However, the first one can be fulfilled by applying rather simple methods [1] while the second one is a hard challenge. This is due to the above mentioned multi-scale hierarchical nature and non-separability of scales causing strong heterogeneity of the local 3D image information.

In [2], we suggested a segmentation of typical structural elements at varying scales. It builds on regions of locally similar orientation and combines morphological smoothing and iterative coarsening. This yields a hierarchical segmentation of the leather into coarse and fine structural elements. The solution found in [2] is however very sensitive w.r.t. the gray value dynamics in the 3D image data.
In order to compare the micro-structure of leather samples from various body parts or even species statistically sound, the segmentation has to be applicable without extensive pre-processing and parameter tuning. Robustness can be gained by applying smoothing methods that are adapted to the goal of defining image regions by similar local orientation. The challenge here is that the space of fiber orientations in 3D – the half-sphere – is not equipped with an order. Motivated by a recent approach for nevertheless defining erosion and dilation on the sphere [3], we suggest new definitions for these morphological base transformations on the space of directions in 3D. Combined into openings or closures, they are versatile smoothing tools.

We present segmentation results for 3D images of purely vegetable tanned leather samples derived by these new morphological smoothing methods.

2 Robust segmentation based on local orientations

2.1 Waterfall on orientations

Neither absolute gray values nor local shape information can be exploited to segment the leather micro-structure. Moreover, the dense and interwoven structure even of soft leather prohibits simple object separation methods.

The local orientation, however, is the suitable feature for defining an object structure as it both fits the known hierarchical build of the leather from collagen fibers as well as the visual impression. There are well-established methods for estimating the local fiber orientation from 3D image data. Out of them, the two based on partial gray value derivatives, e.g. the structure tensor [4] and the Hessian matrix perform best [5]. The result is in both cases a discrete orientation field. That is, the result is another 3D image holding in each voxel the locally preferred orientation. This orientation image is however noisy and contains outliers due to the multiscale structure with components near and below the CT scan resolution, due to noise, and due to CT imaging artefacts caused by the collagen's overall low X-ray absorption contrast. The latter is even worsened by spurious heavy-metal particle inclusions. Local orientation information is therefore usually averaged in order to smoothen the result. For instance, the structure tensor result is usually finally smoothed by a Gaussian. MAVI [6] averages the derived 2nd order orientation tensor in small cubic sub-volumes. Both approaches lack, however, robustness against outliers.

2.2 Median on orientation space

The median is a robust method for determining a preferred orientation in the presence of outliers. Applying the median to the gray value data, however, would erase exactly the local gray value gradient information being essential for local orientation estimation. Thus the median has to be applied to the orientational data.

A mathematical model for the representation of orientations (for example of fibers) in 3D are facing points on the unit sphere [7]. **Fig. 3** shows an orientation as a line through the origin.

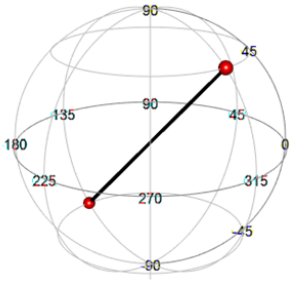

Fig. 3. An orientation in 3D as a line through the origin. The line intersects the unit sphere in the two facing red points.

A set of orientations can be uniquely represented as a set of points $\{x_i; i = 1, \ldots, N\}$ on the upper half of the unit sphere S_+^2, which are called orientation points. A geodesic is the shortest path between two points on the surface of the unit sphere. It is a segment of a great circle. A point on the sphere that minimizes the sum of the lengths of the geodesics to all other orientation points x_i is not susceptible to outliers, since points closer to outliers have longer geodesics to all other points. Finding this point can be formulated as a minimization problem:

$$min_{x\in S_+^2} \sum_{i=1}^{N} arccos\,(x_i \cdot x)$$

The problem of computation of the minimization problem can be solved using a gradient descent algorithm [8]. The point on the sphere that minimizes the sum of all geodesics to all other orientation points x_i is a median on the orientation space and corresponds to a robust preferred orientation of the considered orientations. It should be noted that points close to the equator require special treatment due to the periodicity requirements. **Fig. 4** shows the effect for a toy example.

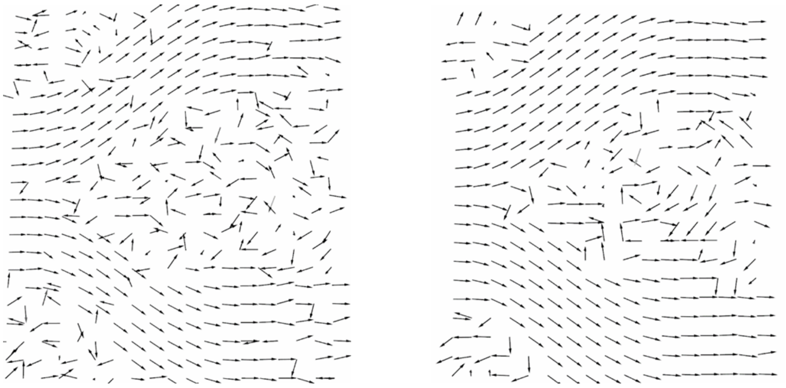

Fig. 4. 2D slice of a 3D vector field of a branching fibers with outliers (left) and same vector field after applying the described method only to the nearest neighbours (right). The resulting vector field is much smoother.

2.3 Smoothing the leather micro-structure

Application of the median filtering to the leather structure (Fig. 5) allows for structure adapted smoothing and thus has the potential to significantly improve the segmentation of individual structural elements.

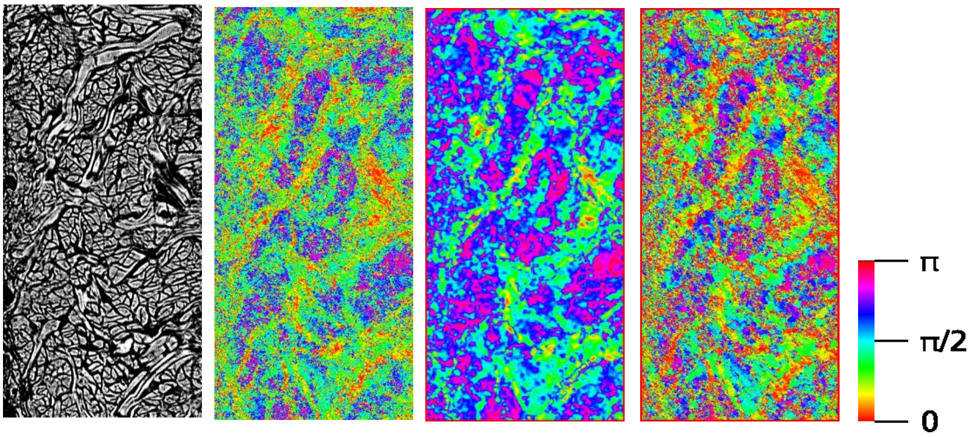

Fig. 5. Virtual 2D xy-slices through the 3D image of the leather sample visualized in **Fig. 1**; Left: Original gray value image; Center left: Colour coded angle to the z-axis (out of the shown plane); Center right: Smoothed by a mean filter on the orientations with 7 x 7 pixel filter mask, structure information is clearly reduced; Right: Smoothed by the new method, same filter mask size, much better following the structure.

2.4 Structural analysis on the collagen fiber bundle scale

The separation of the leather micro-structure into individual bundles as shown in **Fig. 6** can be used along with local, voxel-wise analysis of the gray values, to analyze and compare the structure of leather samples, e. g. from different body parts or different species. Size and shape of the structural elements as well as their sub-structure yield information, e. g. on undulation, branching, thickness, cross-sectional shape, and preferred directions [2].

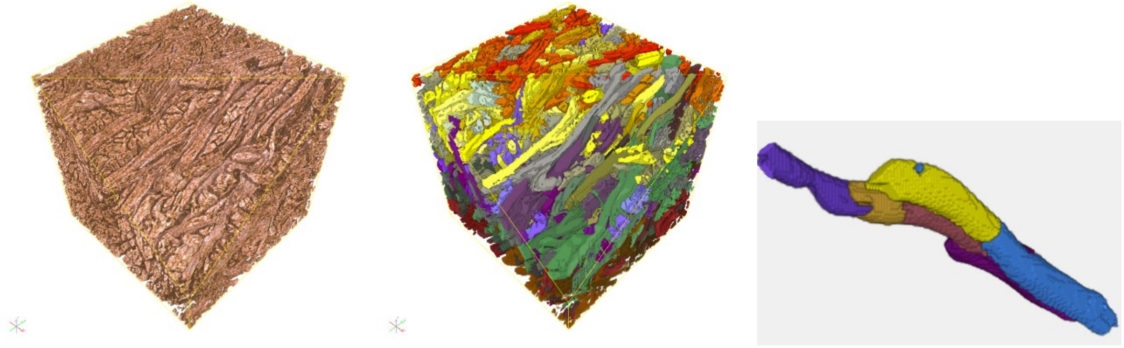

Fig. 6. Left: Volume rendering of a leather sample, 500³ voxels of edge length 3.3 µm; Center: coarse scale segmentation as achieved in [2], colours indicate the individual bundles. Right: Typical smoothed structural element with substructure.

3 Micromechanical modelling on the collagen fiber bundle scale

Realistic finite element simulation of the behaviour of the leather under mechanical load is demanding as it has to incorporate the stretching of bundles as well as all relevant contact and friction mechanisms. Significant contributions towards this goal have been made in [9, 10].

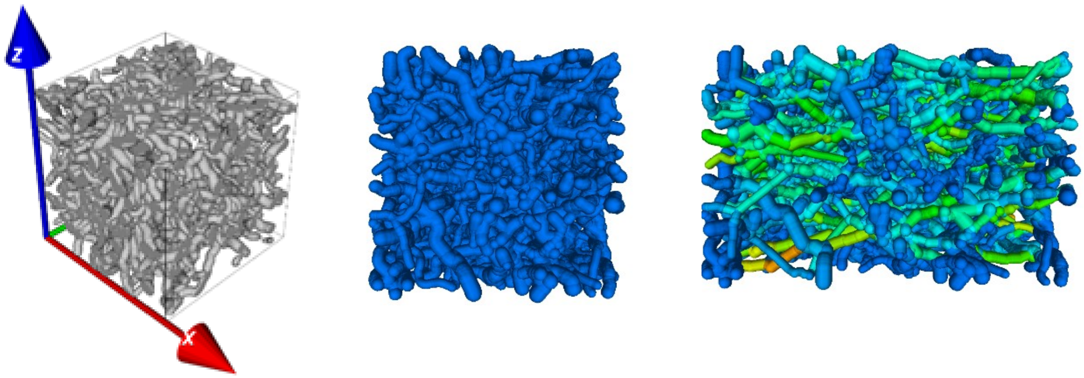

Fig. 7. Left: Virtuell leather structure; Center and Right: Virtual tensile experiment. Center: No load. Right: Loaded, colours indicate local strains – blue low, red high.

Acknowledgements

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