

3D VISUALIZATION AND FINITE ELEMENT MESH FORMATION FROM WOOD ANATOMY SAMPLES PART I – THEORETICAL APPROACH

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Abstract

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The work summarizes created algorithms for formation of finite element (FE) mesh which is derived from bitmap pattern. Process of registration, segmentation and meshing is described in detail. C++ library of STL from Insight Toolkit (ITK) Project together with Visualization Toolkit (VTK) were used for base processing of images. Several methods for appropriate mesh output are discussed. Multiplatform application WOOD3D for the task under GNU GPL license was assembled. Several methods of segmentation and mainly different ways of contouring were included. Tetrahedral and rectilinear types of mesh were programmed. Improving of mesh quality in some simple ways is mentioned. Testing and verification of final program on wood anatomy samples of spruce and walnut was realized. Methods of microscopic anatomy samples preparation are depicted. Final utilization of formed mesh in the simple structural analysis was performed.

The article discusses main problems in image analysis due to incompatible colour spaces, samples preparation, thresholding and final conversion into finite element mesh. Assembling of mentioned tasks together and evaluation of the application are main original results of the presented work. In presented program two thresholding filters were used. By utilization of ITK two following filters were included. Otsu filter based and binary filter based were used. The most problematic task occurred in a production of wood anatomy samples in the unique light conditions with minimal or zero colour space shift and the following appropriate definition of thresholds (corresponding thresholding parameters and connected methods (prefiltering + registration) which influence the continuity and mainly separation of wood anatomy structure. Solution in samples staining is suggested with the following quick image analysis realization. Next original result of the work is complex fully automated application which offers three types of finite element mesh. Tetrahedral mesh is coded for FE analysis with significant gradients and hexahedral mesh is offered for tasks with low gradients. Modified octree code is introduced for future research of anisotropic combined mesh.

ITK, FEM, image converter to FE mesh, hexahedral and tetrahedral mesh, octree, wood anatomy

Main goal of the project, automatic mesh generation from bitmap source is under focus of many research teams. Unfortunately, a lot of them develop useful code just for commercial use. Similar task to our project is conversion of CT images from medical analysis into the finite element meshes which was investigated in many papers. Also many patents were released in this area. We should mention mainly works Finnigan et al. (1994) focused on converting of tomography images into finite element models,

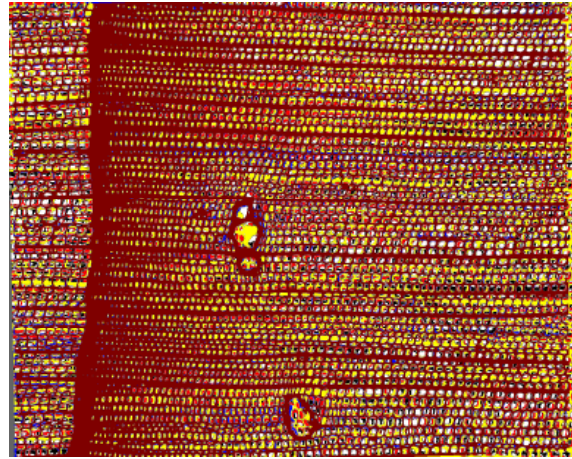
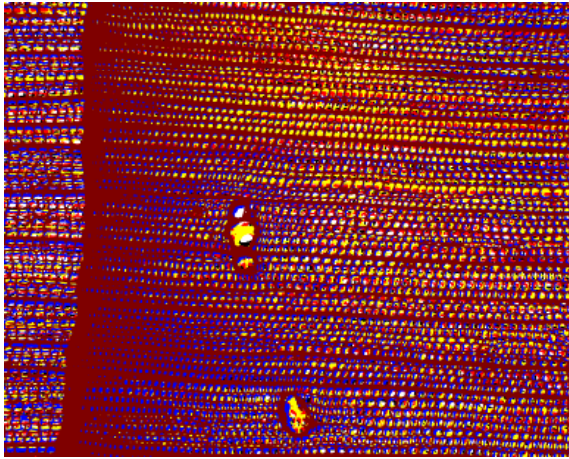
Johnson (1999) aimed on anisotropic representation of scanned object and Usami et al. (2008) who extrapolates the inner volume of shell based geometry.

The work presents implementation of several methods of image registration, filtration and segmentation together with Delaunay method (Delaunay B., 1934), dividing cubes method (Grosland et al., 2002) and modified octree method (Yerry, 1984; Schneiders, 1996).

MATERIAL AND METHODS

Input images obtained by hand way are usually bad shaped and not precisely positioned. Common way to solve this problem is utilization of registration algorithms. In spite of it, the task of registration is very complex problem. Registration process should compensate translation, rotation and rescaling of images.

When the sequence of images just overlay without registering the final composed image proves discontinuity of anatomy elements. For thin closely positioned samples the change can be very small, but more distant samples can consist of very different structure with minimal linkage with other images in sequence (Fig. 1).



1: Sequence of 5 images with 3.3% of continuity on the left and 4.5% of continuity on the right. Left is without registration and right is with implemented registration. Each slice is coloured by different colour.

Registration process compensates the error in position and small deformation of samples. It also admits small discontinuities between two succeeding images. Of course too much discontinuities can lead into more significant error during registration than small deviation of simple overlaid images. When the registration process (by affine transform) is applied the final transformed images can prove relatively small increasing of anatomical elements succession (defined e.g. by integral opening of image measured by one specified colour). In presented example only 0.6% difference in comparison of overlaid images with registration and without registration process will occur for sequence of 3 images and 1.2% difference will occur for 5 images in the whole tested region (Fig. 1). Therefore, the registration process rapidly increases chance to successful realization of the following steps, especially the process of segmentation and forming of the finite element mesh.

In presented application the affine transform procedure with registration based on moments is implemented by itk::AffineTransform class. This class represents an affine transformation by rotation, scaling, shearing and translation of two sequential input 2D images by comparing of them and transforming the second image. Transformation of pixel position is driven by eq. 1 (Yoo, 2004).

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} \cdot \begin{pmatrix} x - C_x \\ y - C_y \\ z - C_z \end{pmatrix} + \begin{pmatrix} T_x + C_x \\ T_y + C_y \\ T_z + C_z \end{pmatrix} \quad (1)$$

x, y, z is original position; C_x, C_y, C_z is center of rotation, T_x, T_y, T_z is vector of translation; M_{ij} are affine transform coefficients.

Filtering plays very useful role in image processing. In programmed application it is used mainly for emphasizing of anatomy structures and suppressing of image noise. Filters in program are formed by thresholding code for separation of background and foreground parts of image or they are formed by convolution techniques. Thresholding separates pixels by simple rule of Eq. 2 for Otsu Filter and Eq. 3 describes thresholding for binary filter.

$$w_{x,y,(z)} = \begin{cases} W_1 & \text{for } w_{x,y,(z)} < Th \\ W_2 & \text{for } w_{x,y,(z)} > Th \end{cases} \quad (2)$$

W_1, W_2 are colour intensity values; $w_{x,y,(z)}$ is output pixel value on position $x, y, (z)$; Th is threshold value

$$w_{x,y,(z)} = \begin{cases} W_1 & \text{for } Th_1 < w_{x,y,(z)} < Th_2 \\ W_2 & \text{otherwise} \end{cases} \quad (3)$$

Th_1 and Th_2 are threshold limits within the image intensities of structure can occur.

Convolution is defined by Eq. 4, 5 (Terry 2004, Žára 2004).

$$P_{x,y} \otimes Q_{x,y} = \sum_{i=-m}^m \sum_{j=-m}^m P_{x-i,y-j} \cdot Q_{i,j} \quad (4)$$

P is 2D image, Q is kernel

$$P_{x,y,z} \otimes Q_{x,y,z} = \sum_{i=-m}^m \sum_{j=-m}^m \sum_{k=-m}^m P_{x-i,y-j} \cdot Q_{i,j} \quad (5)$$

P is 3D image, **Q** is kernel

In presented program two thresholding filters were used. By utilization of ITK two following filters were included. Otsu filter based on `itkOtsuThresholdImageFilter` class and binary filter based on `itkBinaryThresholdImageFilter` were used. Both of them thresholds image according to appropriate threshold. Whereas Otsu filter (Otsu, 1979) automatically computes value of threshold by maximizing of variance in (Eq. 6), binary filter allows defining the user value for sensitive separation of structure from image background.

$$\sigma_b^2(Th) = p_1(Th)p_2(Th)(\mu_1(Th) - \mu_2(Th))^2 \quad (6)$$

$p_1(Th)$ is probability of first interval below threshold Th , $p_2(Th)$ is probability of second interval above the threshold Th , μ_1 resp. μ_2 is mean of the first resp. second interval

Thresholds of binary filter can be manually defined by user or good approximation is automatically computed from mean value of image (Eq. 7) and image covariance (Eq. 8).

$$\mu = \frac{1}{X_{max} \cdot Y_{max} \cdot (Z_{max})} \sum_{i,j,(k)=1}^{X_{max},Y_{max},(Z_{max})} w_{i,j,(k)} \quad (7)$$

X_{max} , Y_{max} , Z_{max} are pixel sizes in x, y, z direction

$$\mu = \frac{X_{max},Y_{max},(Z_{max})}{\sum_{i,j,(k)=1}^{X_{max},Y_{max},(Z_{max})}} (w_{i,j,(k)} - \mu)^2 \quad (8)$$

Thresholding can be defined in two phases of image processing. First phase is just before assembling of 3D image from image series, where user can choose thresholding filters for elimination of different light measurement conditions which lead to incompati-

bility of colour spaces between images within the series and thus problematic or impossible phases of registration, segmentation and mesh forming. Next phase separates the structure from all colour spaces of image series. Contouring is included in application for selecting of pixels on the boundary of wood structure (generally on boundary of structure). Class allows definition of matrix convolution size, but for purposes of the work just one pixel region is tested for image contouring. Meshing of segmented image by tetrahedral elements forms anisotropic mesh. For FE environments good approximation of structure on its boundary is important. Narrow bend around edges of structure is obtained by application of mean filter (`itk::MeanImageFilter`). It is simple convolution with kernel defined by 3x3 matrix of ones multiplied by 1/9. Meshing is realized by Delaunay method (Gelas, 2008; Shewchuk J.R., 1998), which triangulates the significant points of the image and forms unstructured grid of tetrahedral elements.

Two species were chosen for making of microscopic slides: English walnut (*Juglans regia* L.) and Norway spruce (*Picea abies* (L.) Karst.). One block (10 × 10 × 10 mm) of wood from each species has been prepared for cutting. Wood samples were softened by boiling in the 10% water solution of glycerine. Subsequently they were cut on the sliding microtome Leica SM2000R. Series sections were made with 15 µm section thickness. These sections were stained by safranin and mounted in glycerine (Vavřík, Gryc, 2004; Ives, 2001). Images were observed using of Leica DMLS light microscope (objective C PLAN 20 × /0.40). Digital camera Leica DFC280 has been used as a capturing device. Range of interest guidelines in Leica Twain interface were used for alignment of subsequent sections in view field. Images were captured at 1280 × 1024 resolution at 24bit colour depth. The scale of images is 0,47 µm/pixel with light/colour condition in Tab. I.

I: Settings of "DFC TWAIN 6.9.0 for PC" driver capturing:

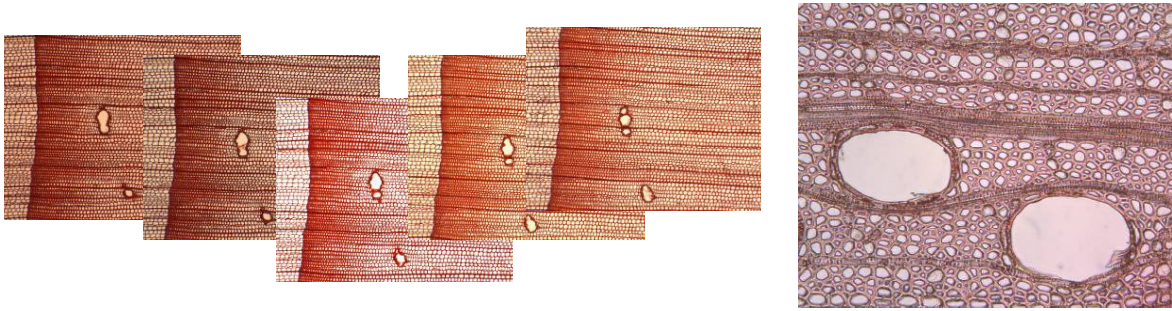
Exp.time	Brightness	Gain	Colour saturation	Black	Gamma	White
248.64 ms	90 %	1.0	1.5	0	0.6	100

Spruce wood is more appropriate for initial image analysis due to simple structure. Walnut wood was used for validation of code robustness because of complex structure of wood.

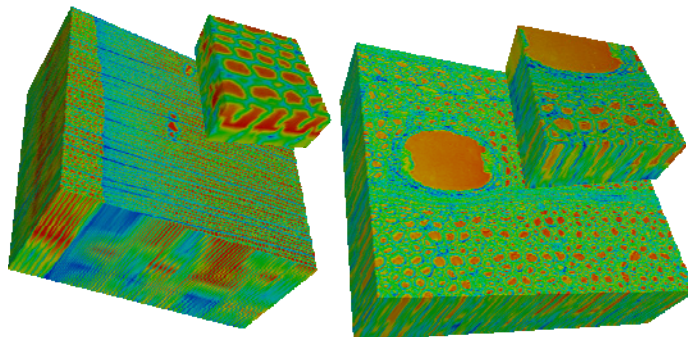
RESULTS AND DISCUSSION

Created program starts by reading of individual images (Fig. 2), which form automatically 3D VTK image with full colour space of each image (Fig. 3).

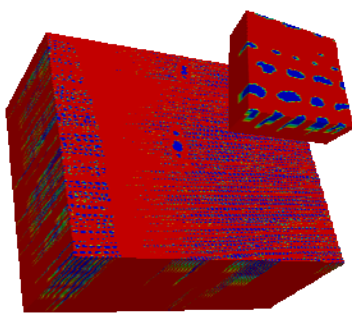
User can process native images by thresholding without any modification. For such purpose the 3D VTK image is used. Thresholding is realized by Otsu filter (Fig. 5) or binary filter (Fig. 4). Pictures demonstrates significant differences between utilization of each filter. In both cases automatic derivation of threshold was used. Thresholds for binary filter are defined by mean value and covariance of the selected region of image (Eq. 9) or can be defined manually by user.



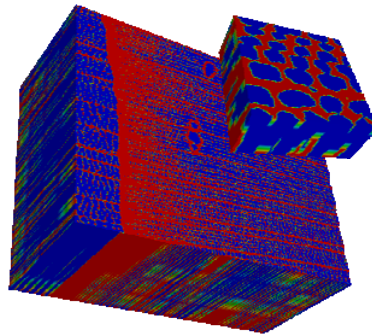
2: Input image series is formed from individual pictures (left spruce wood, right walnut wood). The difference in colour spaces is apparent. Contrast and intensity is not constant.



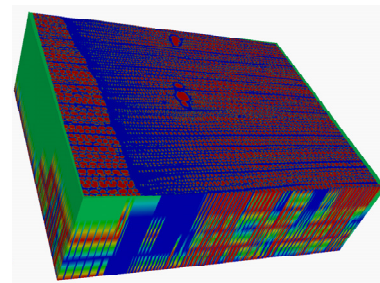
3: 3D VTK image formed from image series with detail (left spruce wood, right walnut wood)



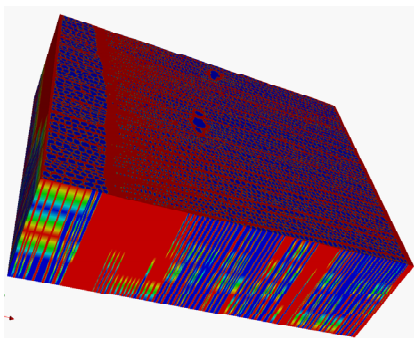
4: 3D VTK image thresholded by binary filter with detail



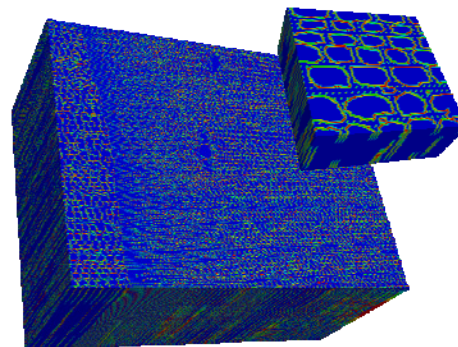
5: 3D VTK image thresholded by Otsu filter with detail



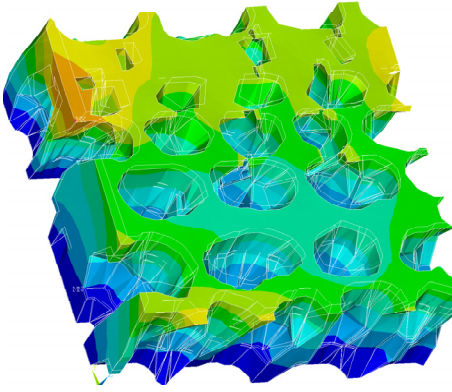
6: 3D VTK image prefiltered and thresholded by Otsu filter with registration



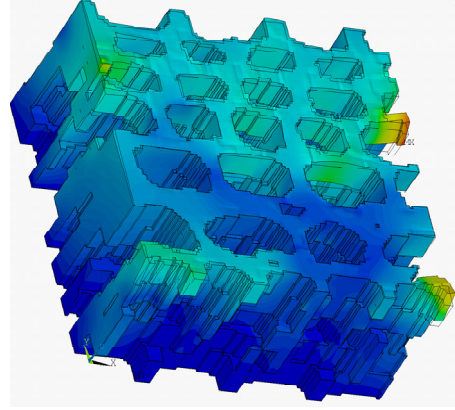
7: 3D VTK image prefiltered with affine registration; green colour represents change (rotation, translation) after registration



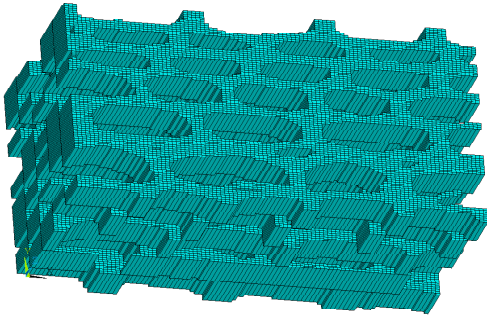
8: 3D VTK contour image prefiltered and thresholded by Otsu filter with detail. Mesh points added.



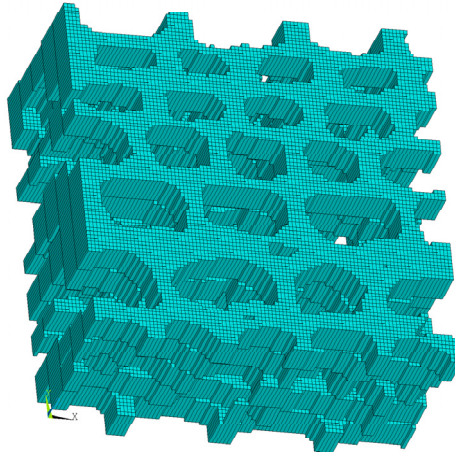
9: Deformation field on tetrahedralized mesh. Source image was registered and prefiltered.



10: Deformation field on hexahedral mesh. Source image was registered and prefiltered.



11: Unstructured hexahedral mesh generated by implemented MIMx code (detail). Source image was not registered and prefiltered.



12: Unstructured hexahedral mesh (25k elements). Source image was registered and prefiltered.

Th1 = 0 or user defined

$$Th_2 = \frac{1}{N} \sum_{i=1}^N w_i + \sqrt{\sum_{i=1}^N \left(w_i - \frac{1}{N} \sum_{i=1}^N w_i \right)^2} \quad (9)$$

In many cases the thresholding of 3D VTK image formed from native images can produce discontinuous image. This effect is caused by colour spaces of individual images which are too far each another. As was mentioned, application offers prefiltering of input images for such case on user request. Prefiltering means thresholding of each image before the 3D VTK image is assembled together. Thresholding is done by Otsu filter or binary filter again. User defines the filter just once for all thresholding operations made in application. Prefiltering unifies colour spaces in input images which results into emphasized contours of structure and improved structure continuity in third dimension. Prefiltered images can be registered by sequence of successive filters and transformed for compensation of small errors in position and deformation. First, registration computes parameters for translation and rotation

of successive image for optimal positioning. In second phase the optimal scale is computed. Optimization runs in 300 steps (number assure robustness for many tested cases). Registered images are written into transformed files with prefix tmp (Fig. 6). Output parameters of registration are printed in standard console. In figure with spruce anatomy samples the change is relatively small (up to 100 px of translation, up to 3 degrees of rotation).

Prefiltered and registered image are thresholded again. In the case, prefiltering is more formal, just for events of residues after prefiltering and registration. Resulted 3D image shows bigger structure continuity (Fig. 7). Registration mainly compensates errors in image acquisition due to deformation of anatomy samples (swelling/shrinkage, relaxation), non-uniform cuts, small failures, etc.).

Next series reader is initiated for reading of the whole native/prefiltered and/or registered image series. User defines the requested region of interest in command line. This region is extracted from

filtered images and appropriate spacing is set. Spacing defines the real distance of voxels in the space. Thus, final mesh will be in metric space with real scale. After spacing the contouring process starts. Contouring plays key role for the following process of structure segmentation. Contouring selects boundaries of cell's lumen. In application the contour is saved with all points on the boundary (lumen). All other points are approximated and reduced for reasonable count of finite elements derived just on pixels from contour filter. Full covering of cells lumen boundary is realized for accurate meshing on curved edges. Thus, a lot of elements are created in these regions allowing FE approximation of regions appropriate for multi(physical) tasks. Points formed by the way mentioned above are triangulated by Delaunay algorithm.

As an alternative to Delaunay tetrahedralization the MIMx code for hexahedral mesh generation was also included. Formed mesh has good quality in comparison with Delaunay triangulation mainly due to regular cells which approximate the image. Cells are very small and are able to describe very thin geometries (thin cell walls, small sized lumens). It is apparent mainly for rough grids of tetrahedralized mesh and big spaced image slices where lumens can collapse together (compare Fig. 9 and Fig. 12). On the contrary hexahedral mesh forms discontinuous boundaries on cell walls. Sharp rectangular boundaries of hexahedral mesh can make difficult the following FE analysis. Edges and points on these boundaries acts as singular points and influence negatively accuracy of solution (compare Fig. 10 where several singular areas occur with tetrahedralized Fig. 9).

Third implemented code for meshing of image voxels forms unstructured grid with anisotropic irregular mesh similar to tetra mesh, but it is formed by divided cubes as in previous code. The mesh is created by declared and modified octree algorithm. Unfortunately, the grid can not be used simply in the FE environments such as ANSYS which demand the structured and well connected mesh. This output can be used for geometry entities just in the moment. Several other tools (e.g. ICEM CFD) are able to form the FE mesh from geometry created by this way. This requires extensive amount of time and computing resources nowadays and is not yet in appropriate form for common utilization.

Difficulties occurred in image processing due to different light conditions among images. Several tests were made with the same light conditions of environment, but variable reflection of test samples and heterogeneous structure lead into incompatible images. Authors suggested staining of wood structure. Nevertheless, long exposition of staining agent results into lumen staining. Main consequence is in emphasizing of cell structures, but also small difference in colour intensity. For optimal samples preparation the immediate consequent image analysis after sample staining is suggested.

CONCLUSION

The paper presents new original complex tool for image processing which process individual images from anatomy samples and forms 3D structure appropriate for quantitative and qualitative analysis. Important supplement of application are several implemented codes for derivation of finite element mesh from image voxels. Code is robust for anatomy samples prepared in high quality. As was proved the application generates mesh with sufficient quality for FE solver, namely ANSYS environment. Due to opened GPL license the code offers to other programmers possibility to create own code for its specific FE environment (ABAQUS, COMSOL, NASTRAN, etc.). Application is still under intensive development. Introduced features are first and most important results of this huge and complicated project.

Created application offers a lot of opportunities for further research in many different scopes. Enumeration of geometry of wood structure allows e.g. revealing of microstructure fractal characteristics such as Hausdorff dimension for crack analysis on such low scale. It is significant challenge to extend analysis in Koňas P. et al. 2008 which tested correlation between fractal dimension of wood anatomy structure and impact energy on 2D space and continue in analysis into 3D space. Analysis of fractal characteristics in full 3D space can finally found causes of failure initiation in wood and it also can reveal the estimators of physical and mechanical properties from these specific geometrical properties.

SOUHRN

3D vizualizace a tvorba konečné prvkové sítě z anatomických vzorků dřeva Část I – Teoretický přístup

Práce shrnuje vytvořený algoritmus tvorby konečné prvkové sítě (KP) odvozené z bitmapové předlohy. Je detailně popsán proces registrace, segmentace a síťování. Pro zpracování obrázků byly použity C++ knihovny STL projektů Insight Toolkit (ITK) a Visualization Toolkit (VTK). Za tímto účelem byla sestavena multiplatformní aplikace WOOD3D uvolněná pod licencí GNU GPL. Je obsaženo několik metod pro segmentaci a především různé způsoby konturování. Byly naprogramovány čtyřstěnné a šestistěnné typy sítí. Jsou zmíněny některé jednoduché způsoby zlepšení kvality sítě. Byla provedena verifikace a testování aplikace na vytvořených anatomických preparátech smrku a ořechu. Jsou

uvedeny metody přípravy anatomických preparátů. Zformovaná síť byla použita v jednoduché mechanické analýze.

Článek diskutuje hlavní problémy obrazové analýzy díky nekompatibilním barevným prostorům, přípravě preparátů, prahování a konečnou konverzi do sítě konečných prvků. Nejdůležitějšími původními výsledky této práce je sestavení uvedených úloh do použitelné automatizované aplikace. V prezentované aplikaci byly použity dva prahovací filtry s využitím ITK; byly implementovány Otsův a binární filtry. Jako nejkomplicovanější úlohou se ukázala otázka přípravy anatomických preparátů za stejných světelných podmínek s minimálním či nulovým barevným posunem a následné definování vhodných prahů (prahovacích parametrů a metod vzájemného provázání jednotlivých řezů (předfiltrace + registrace), které ovlivňují spojitost a především schopnost vydělení anatomické struktury dřeva. Pro tyto účely bylo navrženo barvení preparátů a jejich následné urychlené zpracování. Dalším původním výsledkem této práce je komplexní plně automatizovaná aplikace, která nabízí tvorbu tří typů konečné prvkové sítě. Síť čtyřstěnů je použita zejména pro konečné prvkovou analýzu s výraznými gradienty a síť šestistěnů je nabízena pro úlohy s malými gradienty. Rovněž byla zahrnuta modifikovaná octree metoda především pro budoucí výzkum anizotropních kombinovaných sítí.

ITK, MKP, konvertor obrazu do KP sítě, síť šestistěnů a čtyřstěnů, octree, anatomie dřeva

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