

Methods for 3D Visualization of Bone Tissue in the Proximity of Implants

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Abstract—In this work we present two 3D visualization methods for SR μ CT-scanned volumes of screw-shaped bone implant samples: *thread fly-through* and *2D unfolding*. The thread fly-through generates an animation from slices extracted along the thread helix. Relevant features, such as bone area and bone-implant contact, are computed for each slice and illustrated in a graph. The 2D unfolding maps the implant surface with feature information to a 2D image, providing an instant overview of the whole implant. These visualization methods facilitate the understanding of bone-implant integration.

I. INTRODUCTION

Medical devices such as bone anchored implants are becoming more important for an increasingly osteoporotic population. We aim to improve the understanding of the mechanisms of bone-implant integration. Visualizations of the samples are a great tool for facilitating the visual interpretation. To enable good communication between the people involved in development, production and use of medical devices - computer scientists, material scientists, and medical doctors - each with their own special knowledge, it is of highest importance to provide a common visual platform for a mutual understanding of the problems of implant integration.

Until recently, implants were only evaluated from 2D microscopic images. Such images provide high resolution images but they only represent a small part of the sample and has a high degree of variability due to where the 2D slice is taken. Hence, reliable analysis of bone-implant integration requires 3D sampling of the implants as the whole sample should be included in the analysis. However the complexity of the bone structure makes the 3D imaging task difficult; the bone structure is so fine that we need high resolution.

Micro Computed Tomography (μ CT) is a commonly used tool for imaging bone [1]–[5] and subsequent 3D quantitative analysis. However, when the samples include metallic implants the imaging is made complicated [4]–[7] as the metal absorbs considerably higher amount of X-ray than the bone. This results in artifacts such as an edge gradient surrounding the implant metal [6], [7]. In the recent years, Synchrotron Radiation-based μ CT (SR μ CT) has evolved as a powerful imaging technique in biomedicine and bone studies [4], [6], [8]–[10] as well

as and other disciplines. This technique yields more accurate tomographic reconstruction due to the parallel beam acquisition and higher resolution compared to standard μ CT [10].

However, even with an adequate imaging technique, we also need to visualize the data in a useful way. Commercially available software for 3D visualization are designed for fairly solid and convex objects, since most objects to visualize look that way. This is, however, not the case for the highly porous trabecular bone that surrounds bone implants. Trabecular bone looks like a sponge, and has a huge surface-to-volume ratio.

In this work, we present two visualization methods of imaged volumes of the bone-tissue in the proximity of screw-shaped implants. We image the samples using an SR μ CT device and we use a previously presented segmentation method to segment the volume. The first visualization method, *thread fly through*, follows the implant thread (helix-shaped) from the top of the implant to the bottom and extract slices which are assembled into an animation. Along with the slices, features revealing information about the bone-implant integration are computed from the slices. The second method, *2D unfolding*, maps the implant surface with feature information to an area-preserving 2D image.

II. MATERIALS AND IMAGING

Pure titanium screws (diam. 2.2 mm, length 3 mm), inserted in the femur condyle region of 12-week-old rats for four weeks, are imaged using the SR μ CT device of GKSS¹ at HASYLAB², DESY³, in Hamburg, Germany, at beamline W2 using a photon energy of 50keV. The tomographic scans are acquired with the axis of rotation placed near the border of the detector, and with 1440 equally stepped radiograms obtained between 0° and 360°. Before reconstruction, combination of the projections of 0°–180° and 180°–360° are built. A filtered back projection algorithm is used to obtain the 3D data of X-ray attenuation for the samples. The field of view of the X-ray detector is set to 6.76mm $\times$ 4.51mm with a pixel

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size of $4.40\mu\text{m}$ providing a reconstructed image volume of $14.3 \times 14.3 \times 5.5\text{mm}$ with a measured spatial resolution of about $11 \times 11 \times 11\mu\text{m}$.

III. METHOD 1: THREAD FLY-THROUGH

A. Segmentation

The segmentation and artifact correction method presented in [6] is used for segmentation of the image volumes into three classes; implant, soft tissue and bone tissue. The bone implant is a low-noise high-intensity region in the image volume and is easily segmented by thresholding. We use Otsu's method [11], assuming two classes with normal distribution; a tissue class (bone and soft tissue) and an implant class.

The bone and soft tissue regions, however, are more difficult to distinguish from each other, especially in the regions close to the implant. Due to shading artifacts, the transition from implant to tissue is characterized by a graded transition from high intensity to low. If not removed, this artifact leads to misclassification. We apply a correction by modeling the artifact and compensating for it.

After artifact correction, supervised classification is used for segmenting bone and soft tissue; the respective training regions are marked in one sample from the set and their grayscale values are saved. With the assumption of two normally distributed classes, a linear discriminant analysis [12] is applied to identify the two classes. To reduce the effect of point noise, an $m \times m \times m$ -neighborhood majority filter is applied on the whole image volume after the segmentation.

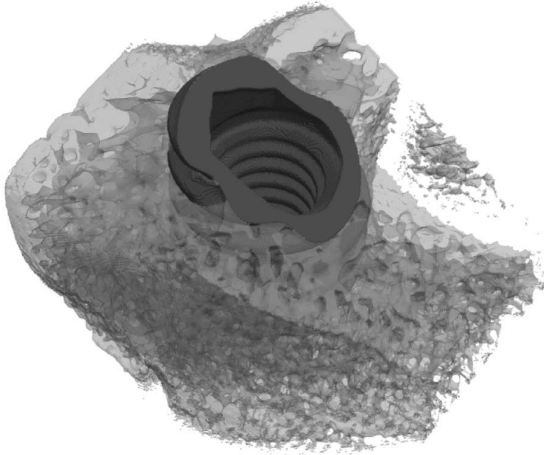


Fig. 1. Rendering of a segmented image volume, showing the implant (darker) and bone tissue (lighter). An upper part of the implant is removed to improve visual impression.

B. Localization of the Thread Path

In order to locate the thread path, we model the implant as a helix, H , following the thread root (TR). For each slice, there is a TR_z is defined as the position on the implant surface where the distance between the implant symmetry axis, ISA , and the implant surface is

minimized. The ISA is calculated by a Principal Component Analysis; each voxel of the segmented implant is considered a data point and its coordinate (x, y, z) is stored in a matrix M . The principal axis where the variance of the segmented implant is largest is computed as the normalized eigenvector with the highest corresponding eigenvalue of the covariance matrix of M . For convenience the image volume is rotated such that ISA is parallel to the z -axis, once the ISA is calculated.

H is modeled in the space as:

$$\begin{aligned} H_z(\alpha) &= \alpha \frac{Z}{\alpha_{\max}} + z_0 \\ H_x(\alpha) &= r_{TR}(\alpha) \cos(\alpha) + ISA_x \\ H_y(\alpha) &= r_{TR}(\alpha) \sin(\alpha) + ISA_y \end{aligned} \quad (1)$$

where $\alpha \in [0, 10\pi]$, z_0 the z -value of the starting point of the helix, Z the height of the implant, ISA_x and ISA_y are the x and y positions of ISA .

The TR -radius (r_{TR}), is calculated as the average of distances from implant roots on one side of the implant silhouette (see Fig 2) to the implant root on the other side divided by two.

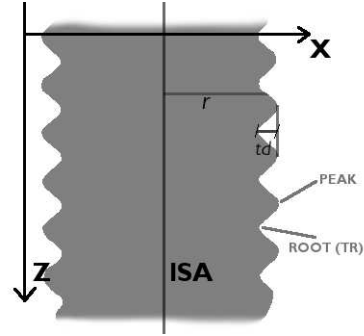


Fig. 2. Silhouette of the screw-shape implant. The implant symmetry axis (ISA), thread root (TR), peak and depth (td) are marked.

C. Features

The regions of interest (ROI) are the implant-interface and the region proximate to it. We present two features related to the ROIs, BA and BC . BA is measured as the percentage of area of bone tissue surrounding a thread from its root to n_{td} thread depths (td) away from the implant. BC is the estimated length of the bone to implant contact in the interface, expressed in percentage of the total length of each crest.

D. Extraction of the 2D slices

The animation, $AN(x, y, t)$, is composed of 2D slices extracted along the helix with α increasing from 0 to $\alpha = 10\pi$. The volume is copied to the 3D texture memory of the Graphics Processing Unit (GPU) and for each t , i.e., frame, a 2D quadrilateral with the vertices v_0, v_1, v_2, v_3 is extracted. The vertices are calculated as one point on $H(\phi)$ and one on $H(\phi + 2\pi)$, where ϕ is an arbitrary angle. The two other points are set to a distance of pd thread peaks away from $H(\phi)$ and $H(\phi + 2\pi)$ respectively.

For each slice, the features BA and BC are calculated. The BA feature is calculated by summing the pixels classified as bone in the relevant region. The BC -feature, on the other hand, requires length estimation. The method used is described in [13].

IV. METHOD 2: 2D UNFOLDING

To know where the implant is in contact with the bone is of great interest. This information can be visualized by marking the interface regions with bone-implant contact, $V_{BC} = (V_B \oplus S) \cap V_I$, where V_I and V_B are the classified implant and bone volume respectively (segmented as described in III-A) and S is a structural element. A rendering of V_{BC} superimposed on the implant-volume, V_I , is shown in Fig. 4(left).

However, such visualizations requires the volume to be shown from several angles to illustrate the whole volume. In order to have an overview we map V_{BC} into a 2D image. This is done by radial sampling from the ISA . Each z-slice of V_{BC} is mapped to a row in the 2D image, I_{BC} .

As the implant does not have a smooth surface, the mapping is not area preserving. Hence a compensation map, C is calculated for which the corresponding pixel in I_{BC} is stretched accordingly. C is computed as $C = C_T C_A$, where C_T is a compensation map for the area difference caused by the outer thread (following the peak) having a larger surface than the inner thread (following the TR) and C_A compensation map for the area difference caused by the slopes of the thread having a larger surface than the root or peak of the thread. C_A is calculated as $\frac{\delta r}{\delta z}$ and C_T as $\frac{\delta r}{\delta(r+td)}$, where r is the axis from the ISA to the implant surface.

V. RESULTS

The majority filter size is set to $m = 3$ as a neighborhood with this size is sufficient to both eliminate the one-pixel wide non-classified interface band and reduce the noise. The number of thread peak depths, n_{td} , is set to 3. The structural element S is set to a 3×3 '+'-shape with ones.

The results involve two animations for each of the five implants, one with the measured BA -feature plotted in a diagram and the other with the BC -feature plotted. An screen shot of one animation is illustrated in 4. The animations show extracted quadrilateral from the SR μ CT volume and the corresponding segmentation. Furthermore an indicator showing the current position of the extracted quadrilateral on the depth buffer presentation of the volume is shown.

The result of the 2D unfolding for one implant is shown in Fig. 4.

VI. SUMMARY AND CONCLUSION

In this work we present two methods for visualizing SR μ CT-scanned volume samples of bone implants with focus on the bone-implant integration. The first method result in an animation composed by slices following the helix formed by the thread of the screw-shaped implant.

Relevant features, such as bone area and bone-implant contact, are computed along the path. The second method maps the the implant surface, with the regions of bone-implant contact marked, to a 2D image.

These visualization methods provides an improved insight to bone-implant integration. The animation provides information about the bone-implant integration over the whole sample in an understandable way. Being able to actually see the 3D structure around the implant will no doubt inspire new measures of the implant integration quality. Furthermore it shows the inhomogeneity of the bone structure. The 2D image of the implant surface gives a direct and area-preserving overview of the contact coverage of the surface.

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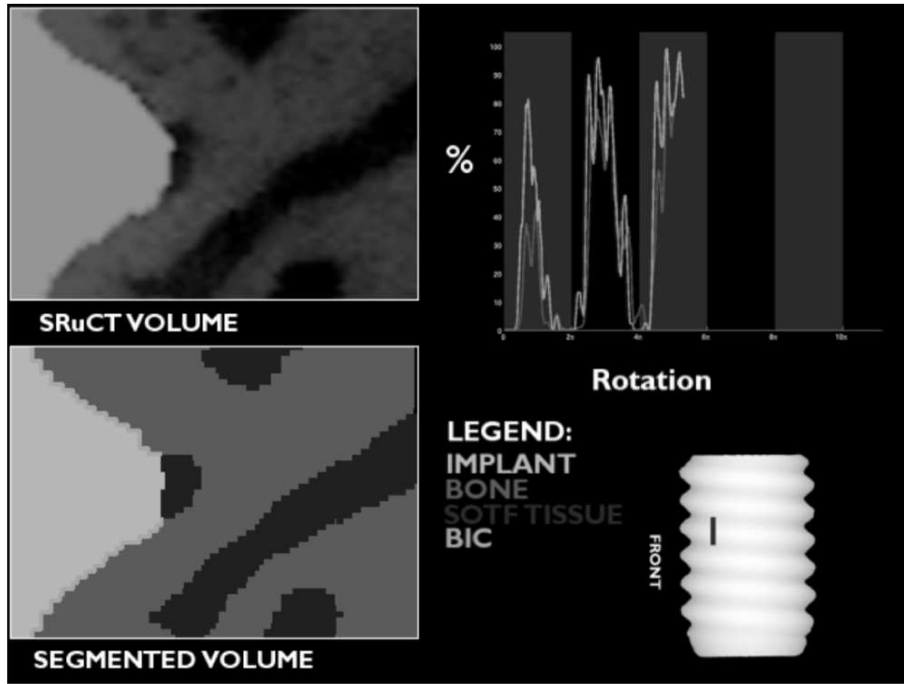


Fig. 3. One frame of the animation. The animation shows extracted quadrilateral from the SR μ CT volume and the corresponding segmentation. Furthermore an indicator showing the current position of the extracted quadrilateral on the depth buffer presentation of the volume is shown.

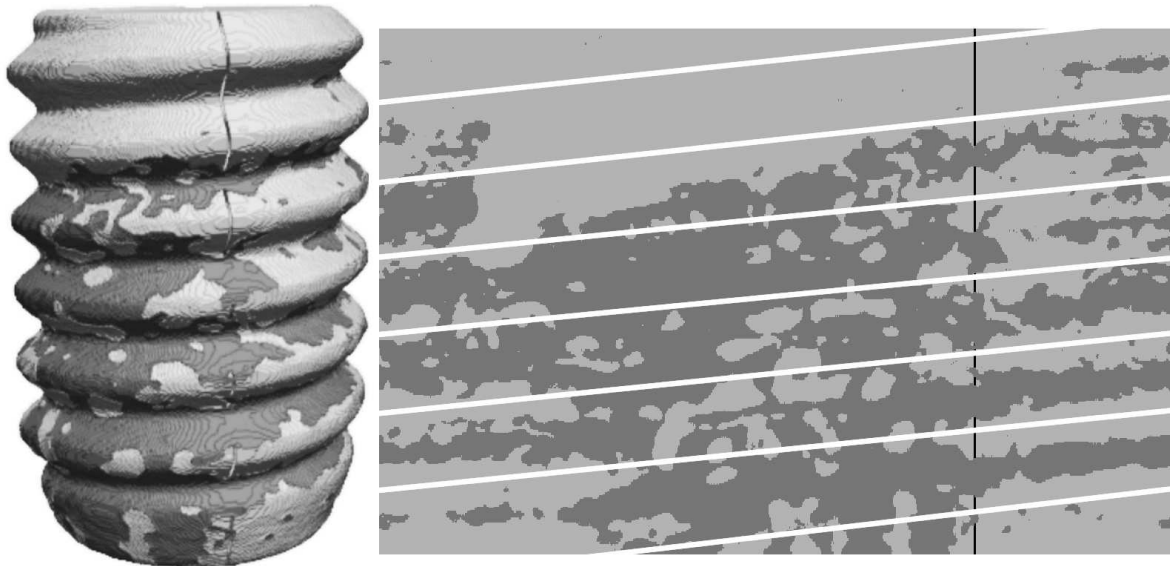


Fig. 4. (Left) Rendered surface of the implant with bone-implant regions marked. (Right) The unfolded surface I_{BC} . White lines superimposed on the mapping show the peaks of the threads. Furthermore, a vertical line show the corresponding positions in the two images.