Fast and accurate DRRs for X-ray based joint surgery planning

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Purpose: Currently available planning systems for joint replacement, are often based on two-dimensional (2D) X-rays and only focus on the determination of the likely size of the prosthesis that could fit the patient's anatomy. Patient-specific biomechanical parameters in such systems are usually neglected as they are difficult to deduce from 2D X-ray images. However, functional and biomechanical information helps to optimize surgical procedures and thus achieve a compromise between balanced joint loading and joint stability to restore optimal dynamic joint function and longevity.

The key challenge lies in the estimation of the three-dimensional (3D) geometry of the patient's anatomy from clinically available X-rays alone. Methods relying on statistical shape models have been shown to be a promising avenue to solve this problem (Dworzak et al. IJCARS 5(2), 2010). In such a scenario, the 3D shape to be reconstructed from the X-ray is parameterized via statistical analysis on a suitable training set (so called statistical shape model or SSM). The optimal parameters are determined via a minimization process, in which the SSM is repeatedly projected to the X-ray plane and the deviation of this projection from the X-ray is quantified.

Up to now, most objective functions measure deviations between boundary features (Baka et al., MedIA 16(6) 2011) of the projected model and the structure in the X-ray (e.g. silhouettes). This has the drawback of requiring a careful segmentation of the structure in the X-ray.

We are extending the previous approach by using 3D volumetric shape models, instead of surface models, in combination with intensity models (e.g. averaged radio-opacity or -translucency) defined on the whole volume of the shape (SSIM). This allows for a direct comparison of the "deformed" model X-rays with the patient X-ray in the optimization process - without accurate prior segmentation.

For efficient optimization an accurate and fast projection algorithm is crucial, since the objective function shall model a good match and will be evaluated many times. Here, we present a hardware accelerated method for SSIM projection.

Methods: *SSIM-based Optimization Process.* Our SSIMs are modeled as deformable tetrahedral meshes (shape) with a polynomial function defined over each mesh cell, representing the distribution of radio attenuation properties (intensity) over any individual cell. The reconstruction/optimization process itself iterates over several steps. First, the SSIM is deformed and a virtual X-ray image is projected from the deformed SSIM instance. This virtual X-ray is then compared to the reference X-ray image. The overall process optimizes the match between virtual X-ray and reference X-ray image. As a result, our process returns the tetrahedral grid, which models the imitated anatomical structures best.

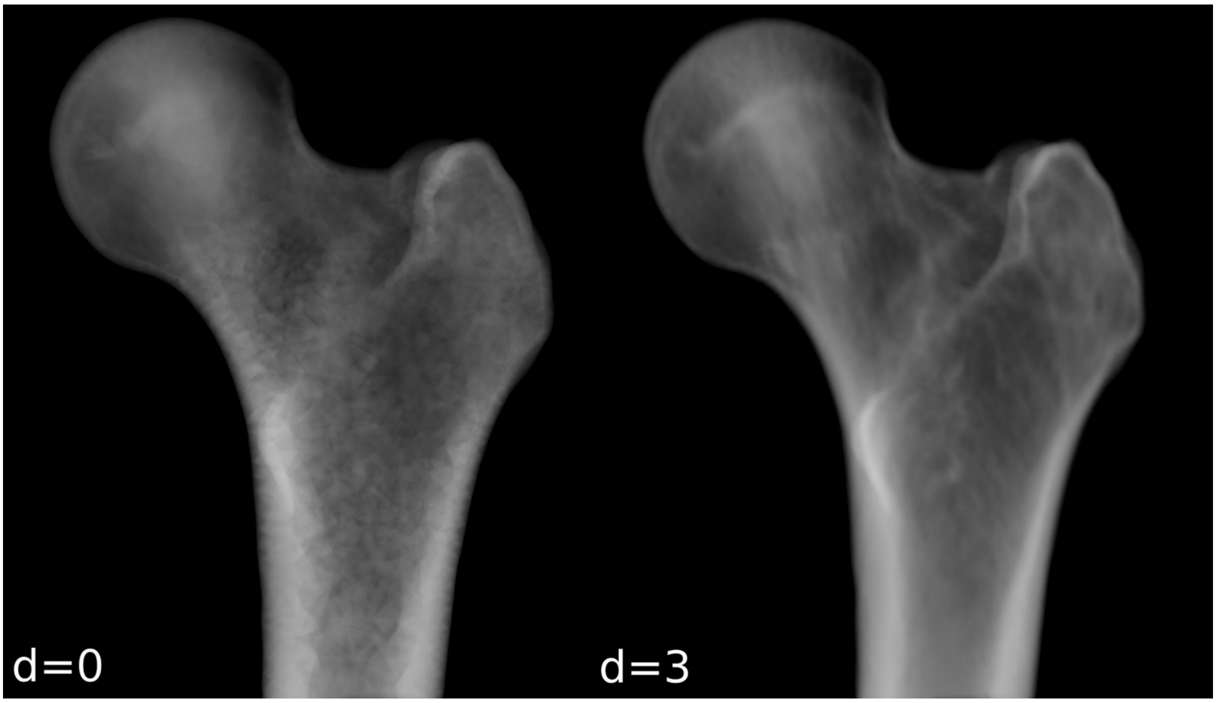
Deforming and projecting SSIMs. The tetrahedral cells of the SSIM are deformed and projected independently in a feed-forward fashion. This allows concurrent processing of individual tetrahedra and is heavily exploited by GPU-accelerated operations. Our goal is to combine both the deformation and projection of the SSIM in a fast, hardware-assisted rendering operation.

Currently, geometric deformation of the tetrahedral cells is performed on the CPU by linearly combining the statistical information of the SSIM. The deformed tetrahedral cells are then pushed to the OpenGL rendering pipeline, where the X-ray image is simulated entirely on the GPU. Our projection algorithm is based on the ray casting approach (Weiler et al., IEEE Trans. UFFC 2003), and features efficient intersection tests in barycentric coordinates. For every tetrahedron, the algorithm first determines barycentric entrance and exit coordinates of virtual X-rays on the tetrahedron, originating at a virtual X-ray source and intersecting the X-ray image plane. It then computes the traversal length of the X-ray within each tetrahedron. For single tetrahedra, the total attenuation is calculated by integrating the attenuation function between the intersection points of the ray (Sadowsky et al., VIS 2005), making use of the previously computed ray parameters. In a final render pass, the attenuation of all tetrahedra is accumulated to form the simulated X-ray image.

Results: We tested the rendering performance of our projection algorithm with different mesh resolutions and polynomial density functions of degree 0 to 3. Rendering speed measurements were taken while rotating the camera around the input-mesh in 10° increments on a test system equipped with a NVIDIA GeForce GTX 560 Ti GPU. The camera viewport was fixed to a size of 800^2 pixels.

On a mesh consisting of 40k tetrahedra, our approach shows average rendering framerates of 149 fps (degree 0), 141 fps (degree 1), 101 fps (degree 2), 56 fps (degree 3). The rendering speed decreases for higher polynomial degrees due to the computational more expensive integration of the attenuation functions. When simulating X-ray images from a higher-resolution mesh of about 4 million tetrahedra, the rendering performance ranges from 4 to 11 fps depending on the polynomial degree of the density functions. Our method is therefore also suitable for projecting higher-resolution meshes.

In order to evaluate rendering results in terms of quality, we compared simulated X-ray images from tetrahedral meshes directly to gold-standard projections of a (CT-) voxel-based ray caster. The accuracy of the simulated X-rays increases with a higher polynomial degree of the density function and higher number of nodes of the tetrahedral mesh (see Figure). We are planning to further investigate the influence of both factors in order to find a suitable ration for the reconstruction process between rendering quality, polynomial degree, mesh resolution and rendering speed.



Conclusion: We presented a method to simulate X-ray images from volumetric deformable meshes. The method produces highly accurate results even for coarse resolutions of the mesh due to the integration of higher-order degree density functions. The reduction of mesh elements is one way of speeding up the 2D-to-3D optimization process in future work. Additionally, we have a achieved significant speedup through implementing the algorithm entirely on the GPU.