Intensity-based Femoral Atlas 2D/3D Registration using Levenberg-Marquardt Optimisation

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Abstract. The reconstruction of the patient-specific 3D anatomy is a crucial step in the computer-aided preoperative planning based on plain X-ray images. The reconstruction is performed by 2D/3D registration of a shape prior into the set of X-ray images. We propose the robust and fast intensity-based 2D/3D registration method of fitting the statistical shape and intensity model of a femoral bone into two orthogonal X-ray images. A user provides a rough initial pose estimation and segmentation of the input X-ray images. We formulate the registration as a non-linear least squares problem, allowing involvement of Levenberg-Marquardt optimisation and combining more similarity metrics at the same time. The GP-GPU acceleration is used for time-consuming parts of the registration. The proposed method has been evaluated on a set of 96 virtual X-ray images ray-casted from CT data sets of eight different bones and using a shape model constructed from 22 bones. The difference between reconstructed and ground truth bone polygonal models has been measured using a symetric Hausdorff distance. The method converged in all tested cases, the accuracy of the reconstruction was 1.28+-1.68 mm on average, which is comparable with other published methods. The pose estimation reached sub-milimiter accuracy in translation and less than 0.5° rotation error around frontal and sagittal axes on average. The error in rotation around the longitudinal axis was less than 2.3° on average.

1 Description of purpose

The identification of the best fitting patient-specific bone implant is one of the common tasks of the preoperative planning in the orthopeadic surgery. Recently, preoperative planning based on plain X-ray images has been brought into focus. For the purposes of the planning, it is important to reconstruct the 3D patient-specific anatomy. That is typically achieved by deformable 2D/3D registration of the shape prior into the set of calibrated X-ray images.

Fast and reliable registration method is needed for femoral interventions planning software intended for clinical use (project Traumatech, TA04011606). Ehlke et al.[2] proposed GPU accelerated registration method focused on the reconstruction of pelvic bone from one X-ray image, but didn't provide an evaluation of the method's accuracy. We propose an improvement of the registration method and perform large-scale evaluation study focused on the reconstruction of femoral bone from two calibrated X-ray images.

2 Method

The 3D bone model is reconstructed using a statistical shape and intensity model (SSIM), which captures femoral shape variability in the population. Generally, the pipeline for the intensity-based 2D/3D registration of the SSIM into the set of calibrated X-ray images is built as a numerical optimisation. In each iteration, digitally reconstructed radiographs (DRR) are rendered from the statistical shape and intensity model. Differences between the original X-ray images and the corresponding DRRs are evaluated using image similarity metrics. The initial pose and shape parameters of the shape model are adjusted to minimise the disimilarities between original and rendered images. The patient-spefic bone model is reconstruted when the value of the similarity metric is minimised.

2.1 *Statistical shape and intensity model*

The statistical shape and intensity model has been created according to Yao.[1] 22 tetrahedral models of femora have been obtained from *Virtual Skeleton Database* CT data sets. Models have been brought into vertex-correspondence and aligned using generalized Procrustes analysis. Principal component analysis on aligned models has resulted in the linear model $y(S) = \overline{y} + \Omega S$, where $\overline{y}$ is the mean bone shape, Ω is the matrix of modes of variation and $y(S)$ is a bone model generated according to the given shape parameters S. The constructed shape model contains 104 thousand of tetrahedra and 26 thousand of vertices. The bone densities are described uniquely in each tetrahedron using Bernstein polynomials of the 3^{rd} degree. Rendering of the DRRs from the shape model is performed using the OpenGL accelerated approach by Ehlke.[2]

2.2 *Deformable registration*

In contrast with Ehlke et al.,[2] we formulate the atlas-based registration as a nonlinear least squares problem. The whole process of the registration comprises from three subsequent optimisations.

In the first stage, the rigid 2D/3D registration of the mean shaped bone to the original X-ray images is performed. This step is involved to avoid local minima and to speed up the following deformable registration. The sum of squared differences (SSD) between corresponding pixels in the original X-ray images and the DRRs rendered from the shape and intensity model is minimised. Formally, the optimisation problem can be stated as follows:

$$\underset{R,T}{\operatorname{argmin}} \left\| g\left(i,x,y\right) - f\left(\left[i,x,y\right],\left[R,T\right]\right) \right\|^2 \qquad (1)$$

where i stands for the index of X-ray and a DRR image pair, x and y are image coordinates. Functions g and f return the pixel intensity values of the original X-ray images and the digitally reconstructed radiographs respectively. The digitally reconstructed radiographs are rendered accordingly to the current translation $T = (t_x, t_y, t_z)$ and rotation $R = (r_x, r_y, r_z)$ parameters.

In the second stage, the pose and the shape parameters of the bone model are optimised simultaneously:

$$\arg\min_{R,T,S} \left\| g\left(i,x,y\right) - f\left(\left[i,x,y\right],\left[R,T,S\right]\right) \right\|^2 \qquad (2)$$

where $S = (s_1, s_2, \ldots, s_n)$ are the shape parameters of the model.

The third stage is used for the refinement of the result obtained in the previous step. Here the optimisation combines multiple image similarity and feature similarity metrics:

$$\arg\min_{R,T,S} \left\| f_{\max}(j) - f(j,[R,T,S]) \right\|^2 \qquad (3)$$

where j is the number of used metric, $f_{max}(j)$ is the maximum value of the j-th metric for an optimal case (i.e. two exactly similar images) and f is a single-valued metric evaluated with respect to the R, T, S parameters. As a single-valued metric the joint histogram normalized mutual information is used, $f(\{0,1\}, [R,S,T])$ is the metric evaluated between j-th X-ray and corresponding DRR image, maximum value of the metric is $f_{max}(\{0,1\}) = 2$. Optionally, user can pick arbitrary count of pseudolandmarks located on the bone silhouette in the original X-ray to accent the anatomy of interest. Consequently, the $f(2,\ldots,n+2,[R,S,T]) = d_{0,\ldots,m}$ are the distances between line segments from focal point to pseudolandmarks and the nearest point on the bone silhouette (distance measure used by Baka et al.[3]), $f_{max}(2,\ldots,m) = 0$, $m = n+2$ and n is the count of pseudolandmarks.

The optimisations are performed using the Levenberg-Marquardt algorithm. The bone density parameters are set to the mean values during the whole registration.

3 Results

The proposed method has been evaluated on a set of virtual X-ray images ray-casted from segmented CT images of femora. We employed leave-one-out methodology; the bone model of currently used X-ray images was always discarded from the training data set of the used shape model. From each CT, 12 virtual X-rays were rendered, rotated around longitudinal axis for $0, 30, 60, \ldots, 330°$, resulting in a data set of 96 images in total. The initial poses of the shape model were generated randomly with a uniform distribution. The maximum difference between the initial and the ground-truth pose was limited to $10°$ rotation and $10\,\mathrm{mm}$ translation in each direction and along each axis.

The method converged in all tested cases. The largest amount of dissimilarity between X-rays and digitally reconstructed radiographs was reduced by the first and the second optimisation, while the fine details of the bone shape were obtained using the mutual information metric based optimisation, as shown in Figure 1 and in our YouTube video *.

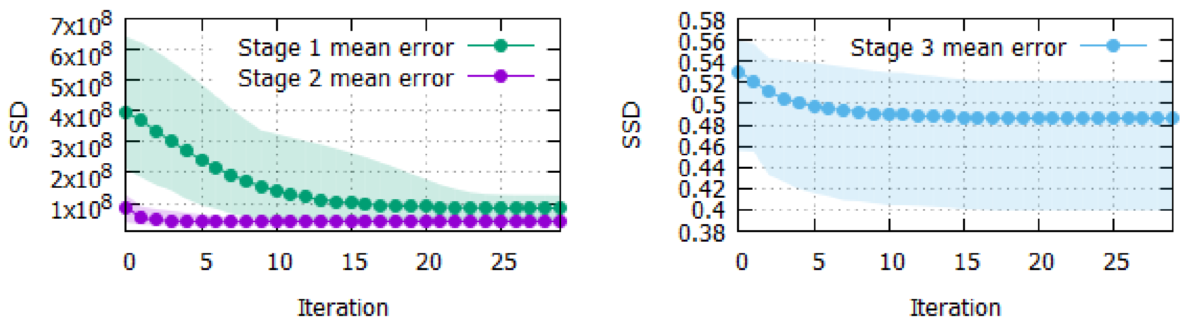

Fig 1 Metric values during the registration: (left) SSD between corresponding pixels in each iteration; (right) SSD between the mutual information evaluated on corresponding X-ray and DRR images and the maximum possible value of the mutual information-based image similarity metric.

For the evaluation of the registration accuracy, we measure the mean and maximum symetric Hausdorff distance between the surfaces[4] of the ground-truth and the reconstructed bone model. The results of the evaluation on 96 cases are shown in Figure 2 in the form of the empirical cumulative distribution functions. The average mean error of the reconstructed bone was $1.28 \pm 1.68\,\mathrm{mm}$, average maximum error was $7.38\,\mathrm{mm}$. This accuracy was reached without marking the anatomy of interest. On average, 3515 digitally reconstructed radiographs were rendered per registration.

4 New or breakthrough work to be presented

We adopted the Ehlke's method originally designed for the reconstruction of the pelvic bone, and further improved the method by formulating the registration as non-linear least squares problem, by

*https://youtu.be/SfiCX6ETF8w

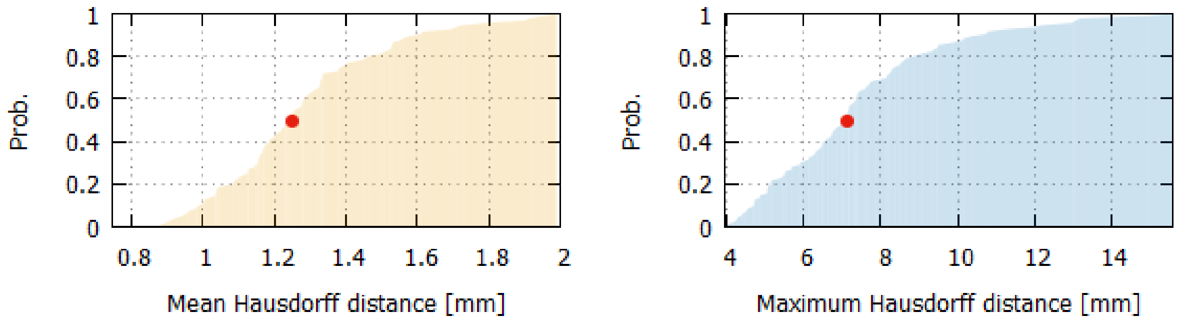

Fig 2 Cumulative distribution of the mean symetric Hasdorff distance[4] (left), cumulative distribution of the maximum error (right). The average case is highlighted by the red point.

involvement of Levenberg-Marquardt optimisation method and usage of multiple image similarity metrics. We used the improved method for a double-view reconstruction of femoral bones from two calibrated x-ray images. We performed a large-scale evaluation study on a set of 96 pairs of virtual X-ray images. We are currently working on the evaluation using real X-ray images. This work has not been submitted for publication anywhere else, certain GP-GPU acceleration aspects will be discussed at Shape Symposium 2015.

5 Conclusions

We have proposed the improved method for multiview intensity-based 2D/3D reconstruction of the femoral bone. The method assumes that at least a rough initial estimation of the pose and approximate segmentations of the bone in the X-ray images are given, as the method proposed by Ehlke.[2] Formulation of the registration as a non-linear least squares problem and optimisation using Levenberg-Marquardt algorithm leads to the reliable 2D/3D reconstruction method. It converged on all tested X-rays. Ehlke[2] reported that for pelvic bone reconstruction using his original optimisation aproach approximately 6000 digitally reconstructed radiographs were rendered on average. In comparison, 3515 digitally reconstructed radiographs on average were needed to reconstruct the femoral bone in our case, which results in a significant speed up of the reconstruction. The proposed method reached 1.28 ± 1.68 mm reconstruction accuracy, which is comparable to other methods that can be found in a brief summary of the state of the art methods presented by Baka.[3] Moreover, the least squares formulation of the registration allows to combine more image similarity metrics at the same time, which can be exloited for the manual selection of the anatomy of interest.

References

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