Model-based Radiostereometric Analysis Using Intensity-based 2D/3D Registration Pipeline: Feasibility Study

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Abstract

Model-based radiostereometric analysis (MBRSA) methods exploit, in most cases, feature-based 2D/3D registration. In this paper we focus on a feasibilty of the intensity-based 2D/3D registration approach applied in MBRSA. To evaluate the feasibility, we created a data set containing stereo pairs of both synthetic and real radiographic images of a metallic radius bone implant. Evaluation, we performed and present, reveals sufficient accuracy of the intensity-based registration pipeline and its robustness to image artifacts. The results obtained using synthetic radiographs show comparable accuracy with the feature-based non-overlapping area (NOA) approach. The registration process using real X-Ray images did not require preprocessing of the input radiographs neither was significantly affected by the presence of the metallic bone screws. This study presents an introductory part of an ongoing research.

Keywords: Radiostereometric analysis, Implant migration, 2D/3D registration, Levenberg-Marquardt optimization

1. Introduction and Related Work

Radiostereometric Analysis (RSA), proposed by Selvik [1], is a method for monitoring the fixation of an implant within a bone [2]. The analysis allows an identification of a micromotion between the implant and the bone. The RSA method is indicated especially in cases of total joint replacement, such as total knee (TKA) or total hip (THA) arthroplasty [3, 4, 5]. The method is based on pairs of stereo radiographs. The traditional approach exploits tantalum markers injected into the bone together with markers attached to the implant. The tantalum markers are shown in Figure 1. Markers positions in the 3D space are obtained by triangulation from the radiographic stereo pair. The patient commonly undergoes several following-up examinations during the two years after the intervention [6]. The implant migration is revealed when the relative pose between the bone markers and the implant markers differs among the examinations.

However, several issues exist related with attaching markers to the implant. The markers attached to the implant may be occluded in the radiographs by the implant itself, the marked implants are significantly more expensive, and moreover, the implants may be weakened by the markers [2]. These issues are addressed by the model-based radiostereometric analysis (MBRSA), proposed first by Valstar [7]. The method is based on a 2D/3D registration of a virtual implant model into the radiographic stereo pair instead of marking the implant, while the bone markers remain involved.

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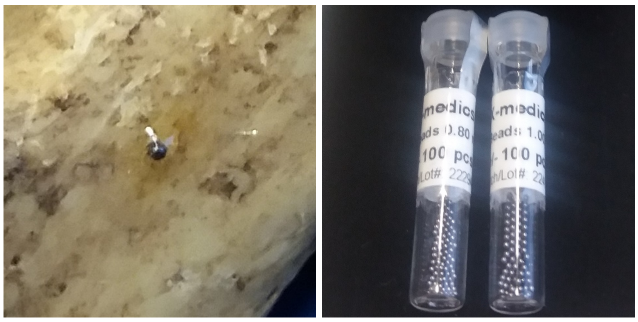

Figure 1: A tantalum bead of 0.8 mm in diameter glued to a dry cadaveric bone (left). A packing of two hundred tantalum markers (right).

Most of the model-based RSA methods depend on *feature-based* registration, exploiting the edges detected in the radiographs [7, 2, 4]. We have recently proposed an *intensity-based* method for the 2D/3D registration of a bone atlas into the X-Ray images [8]. The main goal of this preliminary study is to verify that the intensity-based registration is feasible in terms of the model-based radiostereometric analysis using the previously proposed approach.

2. Intensity-based Registration Method

The aim of the registration is to recover an accurate pose of the implant model within the 3D space of the stereo radiographic pair. A rough initial pose estimate provided by a user is required. The proposed method is designed for binary images.

The registration is performed as an iterative optimization. Digitally reconstructed radiographs (DRR) are rendered from the implant model in current pose in each iteration. A similarity between the DRR images and the radiographs is evaluated using the mean square error (MSE) measure. The rotation and translation of the model are consequently adjusted to minimize the differences between the real and the virtual radiographs. The resulting pose of the implant model is obtained when the dissimilarities are minimal.

The registration is formulated as a non-linear least squares (NLS) problem:

$$p^* = \arg\min_p \frac{1}{N} F(p)^T F(p) \quad (1)$$

where $p = (R, T)$ is a pose vector formed by the rotation and translation of the implant model, N is a count of pixels contained in the radiographs and $F(p)$ is a vector of residuals between the original X-Ray and DRR images:

$$F(p) = \begin{pmatrix} \mathrm{vec}(\mathrm{DRR}_{AP}\ (x) - \mathrm{XRay}_{AP}\ ) \\ \mathrm{vec}(\mathrm{DRR}_{LAT}(x) - \mathrm{XRay}_{LAT}) \end{pmatrix} \quad (2)$$

where $|F(p)| = N$. The optimization is solved using the Levenberg-Marquardt algorithm [9], which is a highly effective method in terms of 2D/3D registration [10]. The accuracy of the method strongly benefits from the optimization on a pixel level [8]. The optimization can be interpreted as a minimization of a non-overlapping area (NOA) between the real and virtual radiographs, similarly to the approach proposed by Valstar [7].

3. Experimental Results and Discussion

3.1. Synthetic Radiographs

The accuracy of the intensity-based method was evaluated using synthetic radiographs. The radiographs were generated as binary images from a polygonal model of a radius bone implant consisting of 71,689 vertices and 143,762 faces. The virtual X-Ray images were of size 849 × 206 and 873 × 277 pixels respectively with horizontal and vertical pixel spacing equal to 0.143 mm. Consequently, the vector of residuals $F(p)$ was formed by 416,715 elements. The registration was repeated 10 times, initialized with various randomly generated pose estimates. The differences between the initial and the ground-truth poses were limited to ±9 mm in translation and ±9 ° in rotation. The registration took 55 iterations on average.

Table 1: Distributions of translational errors (n = 10).

	T_x [mm]	T_y [mm]	T_z [mm]
Mean	0.033	-0.010	-0.068
Std. Dev.	0.139	0.013	0.106

Table 2: Distributions of rotational errors (n = 10).

	R_x [°]	R_y [°]	R_z [°]
Mean	-0.107	-0.406	-0.009
Std. Dev.	0.133	0.566	0.231

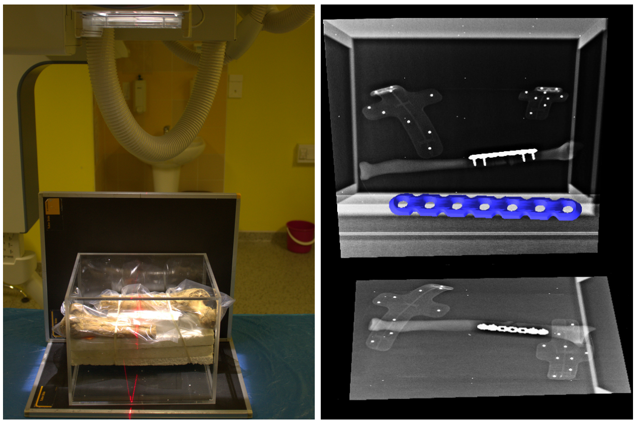

Figure 2: Illustration of the experimental setup placed in the X-Ray machine (left). The actual calibrated radiographs capturing the bone model with attached implant (right). In front of the radiographs there is a virtual model of the implant, highlighted by a blue color.

The results are shown in Table 1 and Table 2 as translational and rotational error distributions with respect to individual axis. The highest rotational and the lowest translational errors occurred in case of the y axis, which corresponds to the longitudinal axis of the implant model. This is an expected result as the virtual X-Ray images were taken approximately in xy and yz planes in the space of the implant model.

Table 3 shows comparison between the intensity-based registration pipeline and the feature-based NOA approach. The intensity-based method has slightly larger rotational error, but on the other hand is more accurate in translation. However, this comparison is rather tentative according to a different nature of evaluation data sets and a different kind of involved implants. The radius bone implant is not significantly asymmetric in comparison with implants dedicated for THA and TKA interventions.

Table 3: The largest standard deviations for translation and rotation.

	T [mm]	R [°]
NOA (Valstar [7])	0.221	**0.524**
Proposed approach	**0.139**	0.566

3.2. Real Radiographs

An illustration of the experimental setup is shown in Figure 2 left. The radiographs were taken using the X-Ray cassettes of size 35 × 43 cm and calibrated using a custom made biplanar RSA cage. The captured object is placed on the Styrofoam inside the Plexiglas calibration cage. For the real-world evaluation of the method we used a plastic model of a fractured radius bone with a metallic bone plate. The bone plate was attached to the plastic model using metalic screws. Radiographs of the model were taken serially from anterior-posterior and lateral views and calibrated using the DLT approach [11]. The actual radiographs are shown in Figure 2 right.

A rough initial pose of the implant model in the 3D space was set interactively. The initial pose is shown in detail in Fig-

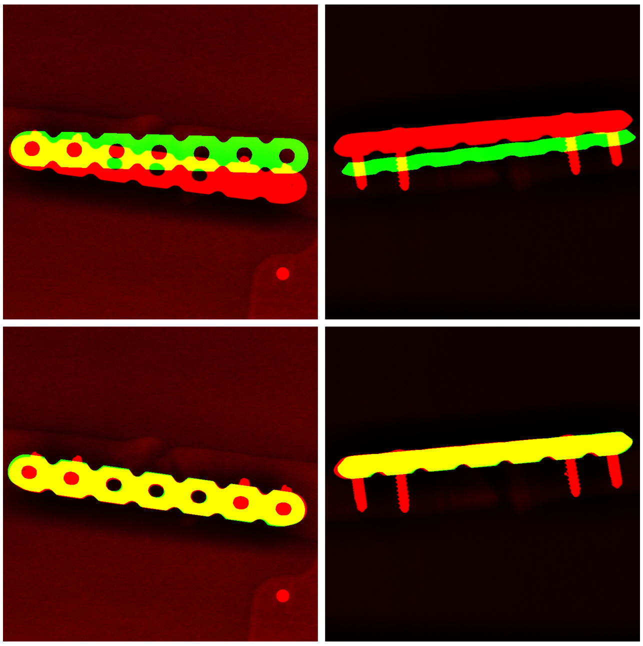

Figure 3: Initial pose of the implant provided by the user (top). The resulting pose recovered by the proposed 2D/3D registration method (bottom).

ure 3 in the top row. The original radiographs are visualized by a red color and overlayed by green shaded DRR images rendered from the implant model. The overlapping area is emphasized by a yellow color.

Although the method is dedicated for binary images, the original radiographs were used for the registration instead. This was possible due to high contrast between the metallic bone plate and the surroundings. The registration process took 72 iterations, the final result of the registration is shown in Figure 3 in the bottom row. It can be seen that the registration did not fail due to lower contrast surroundings, nor due to the high contrast bone screws which are not a part of the implant model.

4. Conclusion

We have verified that the intensity-based 2D/3D registration is clearly feasible in terms of model-based radiostereometric analysis. Moreover, the radiographs are suitable for the registration without further processing. The quantitative evaluation based on synthetic X-Ray images revealed that the intensity-based method and the feature-based non-overlapping area approach have tentatively comparable accuracy. The currently ongoing work is focused on the real-world accuracy evaluation using the implants dedicated for the THA and TKA interventions. The registration pipeline is publicly available at http://www.fit.-vutbr.cz/~iklima/prods.php?id=458 and http://www .fit.vutbr.cz/~iklima /prods.php?id=505.

ACKNOWLEDGEMENTS

This work has been supported by the Internal Science Fund of Brno University of Technology grant no. FEKT/FIT-J-17-4745 Intermodal Registration of 3D Data in Health-care and by the Technology Agency of the Czech Republic grant no. TA04011606 Modern Image Processing Techniques and Computer-based Planning in Trauma Treatment. The authors thank the 3Dim Laboratory s.r.o. for providing the radius bone plate and its virtual model and the University Hospital in Ostrava for capturing the experimental radiographs.

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