Registration of bone surfaces, extracted from CT-datasets, with 3D ultrasound

S. Winter[1], B. Brendel[2], A. Rick[3], M. Stockheim[4], K. Schmieder[5], H. Ermert[2]
[1]Institute of Neuroinformatics, Ruhr-University Bochum, Germany
[2] Institute of High Frequency Engineering, Ruhr-University Bochum, Germany
[3] ZN Vision Technologies AG, Bochum, Germany
[4] Department for Orthopedic Surgery, Ruhr-University Bochum
[5]Department for Neurosurgery, Ruhr-University Bochum, Germany

Susanne.Winter@neuroinformatik.ruhr-uni-bochum.de

Abstract—*An essential task of computer assisted surgery is the registration of preoperative image data with the coordinate system of the operating room. This can be reached by using intraoperative imaging and registrating preoperative and intraoperative datasets. For intraoperative imaging ultrasound is a powerful tool due to the lack of ionizing radiation and because of its fast, inexpensive and easy data acquisition. We propose a surface volume matching algorithm for the registration of bone surfaces and ultrasound volume data. The bone surface is estimated from the preoperative CT data by taking into account that ultrasound only shows parts of the bone surface. By our method reliable matching results are obtained. They are shown with data of the lumbar spine.*

Keywords—*registration, intraoperative imaging, ultrasound, spine, computer assisted surgery*

Introduction

Intraoperative navigation is used today for many surgical procedure [1] in order to increase the precision and to reduce the intervention time and invasiveness of surgical treatments.
Preoperative image data, mostly Computer Tomography (CT) or Magnet Resonance Imaging (MRI), is used for planning the operation. To use this data for navigation a registration of the data within the coordinate system of the navigation system is required.
There exist many different methods for registration [2, 3, 4], most of them are based on landmarks, e.g., anatomical structures or fiducial markers. For the registration these landmarks must be marked on the preoperative data and during the operation they must be referenced with a pointing device. This procedure is time consuming.
The accuracy of these registration methods depends on the number of points and on the ability of these points to move with respect to the structure of interest [5, 6]. The most precise registration for surgical treatments at the bone can be reached with fiducial markers which are preoperatively fixed to the bone with screws, but this increases the invasiveness.
The use of intraoperative imaging can solve these problems. Some systems work with intraoperative CT or MRI [7, 8]. The registration methods use the complete anatomical information or match the pre- and intraoperative image data by first segmenting surfaces and then register these surfaces [9]. The disadvantages of these systems are the high costs and the radiation exposure (CT).
Intraoperative ultrasound could be the solution [10-14], with the advantages of a fast and cheap data acquisition. Additionally, it does not require much space in the operating room in contrast to intraoperative CT or MR and can be easily handled.
The main problem of ultrasound is the low imaging quality, however the bone surface can be visualized because of the strong reflection at the bone-tissue interface.
We propose an algorithm for the registration of bones which takes into account the properties of the ultrasound imaging like specular reflection and speckle.

Materials and Methods

A concept for the integration of ultrasound as an intraoperative imaging modality for the registration of the patient position to preoperatively acquired data sets is shown in figure 1.

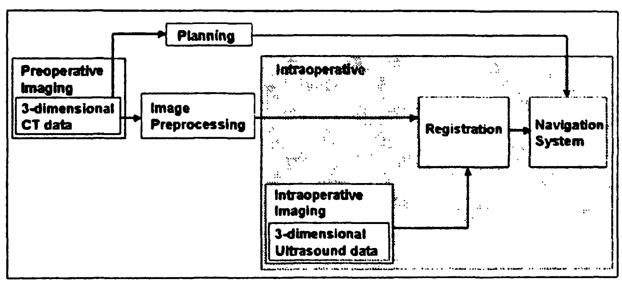

Figure 1: Concept of the integration of ultrasound into navigated surgery.

The first step is the acquisition of preoperative CT datasets which are used for the planning of the surgical treatment. This CT-data can be preprocessed before the surgical intervention in order to speed up the registration procedure during the intervention.
During surgery an ultrasound probe, which is connected to the navigation system and which has been calibrated beforehand [15-17], can be used at any time to register the two coordinate systems of the preoperative dataset and the intraoperative patient position in the navigation system By using a fast registration algorithm this step can be repeated as often as necessary during the intervention, e.g., after any repositioning or movement of the patient.

The registration process of this ultrasound dataset and the CT dataset needed for this application must be fast, robust and precise. Most registration algorithms can be formulated as an optimization problem to find the coordinate transform that maximises some kind of optimization criterion between the two modalities.

In order to obtain a fast and robust registration procedure the optimization criterion must be well adapted to the particularities of the ultrasound data. To avoid sensitivity to speckles a significant number of voxels must contribute to the matching, but unfortunately, voxels inside bones or hidden behind bone surfaces do not provide useful image information. On the contrary, the tissue-bone interface [18] produces a very strong signal in the ultrasound data due to the strong change in elasticity. Because of the total reflection at the tissue bone interface only the first bone surface reached by the ultrasound wave can be imaged. As the reflection at the bone surface is almost perfectly specular, it can be compared to a mirror for the ultrasound waves. Therefore the ultrasound sensor detects only surfaces which are nearly orthogonal to the direction of the ultrasound propagation.

When combining these effects it can be concluded that an optimization criterion well suited for ultrasound-CT registration must concentrate on all surface elements on the tissue-bone interface surface that are perpendicular to the ultrasound propagation and not hidden by other bone surfaces which are between the surface element and the ultrasound probe.

This choice of points has significant advantages, as the number of points that satisfy this criterion is a good trade-off between a landmark based registration which would suffer too much under the severe noise due to speckle in the ultrasound and a complete volume to volume registration, which would be computationally very intensive but would not improve the results as the rest of the volume contains almost no relevant information for the registration.

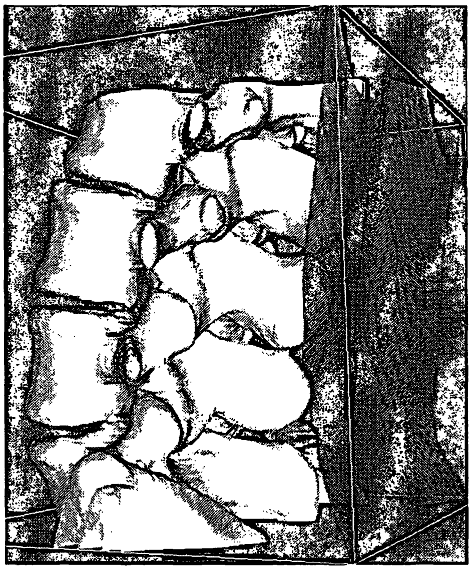

Figure 2: Complete bone and skin surface extracted from CT data by thresholding.

In order to increase the speed of the registration algorithm all expensive processing steps should be done off-line on the preoperative dataset rather than during the registration itself. Therefore the surface elements that satisfy the above conditions are extracted from the preoperative dataset.

The first step of the preprocessing is the extraction of the bone and skin surface by simple thresholding in the CT dataset (see figure 2). The next step is the extraction of the surface elements that are visible from the skin surface (see figure 3). Finally the surface normals are calculated for each of the remaining visible elements and all the elements which are not oriented nearly perpendicular to the skin surface are discarded.

During the intraoperative registration we propose to use a surface-volume registration using the points of the remaining surface elements and the complete ultrasound dataset for the determination of the optimal coordinate transform. The advantage of this process is that the ultrasound dataset acquired intraoperatively needs no preprocessing.

We define the optimization criterion as the average ultrasound gray value which is covered by the point set P extracted from the preoperative data.

The optimisation parameters are three rotation angles (α, β, γ), where $R(\alpha, \beta, \gamma)$ is the rotation matrix, and the elements of a 3-dimensional translation vector $\bar{s}$. As we work on discrete data and rotate the surface points, we use a simple and fast Nearest Neighbor interpolation to determine the gray value of the corresponding locations in the ultrasound data.

For the implementation the surface point set P is described as N points $p_n(x_n, y_n, z_n)$ where x_n, y_n, z_n are the 3-dimensional coordinates of a point $\bar{p}_n$. This point set is superposed to the ultrasound-dataset and the optimization criterion is computed. as follows:

$$o = \frac{1}{N} \sum_{n=1}^{N} u(R \cdot \bar{p}_n + \bar{s}), \qquad (1)$$

where $u(\bar{p})$ is the gray value of the ultrasound image at the location $\bar{p}$.

Figure 3: Slice of CT data, the surface elements that are visible for the ultrasound are marked white.

Experiments and Results

The algorithm was implemented in matlab and C and tested on CT and US data acquired on a lumbar spine preparation. The CT dataset had a 0.39x0.39 mm² in plane resolution and a 3 mm slice thickness with 2 mm spacing. The field of view was 200x200 mm². The ultrasound images were acquired using a 3.5 MHz curved array. A series of B-scans were acquired with 1mm spacing in cranio-caudal direction and 0.5x0.5 mm² in plane voxel resolution.

The segmentation of the bone leads to approximately 60,000 points which satisfy the above criterion for inclusion into the registration process. The threshold for the bone segmentation was 200 Houndsfield Units [19].

We implemented different methods for the optimisation. A simple gradient descent method works well if the starting position is within 15 mm of the optimal match. Rotational deviations of about 10 degree around the longitudinal axis and about 20 degree around the other two axis can be corrected by this method. The gradient descent method is fast and takes about one minute on a 650 MHz Processor where the algorithm itself is not optimized.

We further implemented an evolutionary CMA-algorithm (covariance matrix adaption) [20]. The use of evolutionary algorithms is the avoidance of convergence to local maxima., so that the radius of convergence is larger. A special feature of the CMA-algorithm is its automatic adaptation of the stepsize of parameter variation.

The algorithm can match the surface if it is rotated about 30 degree around one of the axis. In Figure 4, a 3-dimensional view of the registered surface elements is visualized. Figure 5 shows the projected surface points before and after the registration with a rotation around the longitudinal axis. The underlying ultrasound image is an axial slice where the spinous process and the lamina is imaged. In the upper image of figure 5 the surface was rotated around the medio-lateral axis, the ultrasound slice is a sagital view of the lumbar spine. The lower image shows the result after registration. In the middle image the surface is shifted 40 mm. The evolutionary algorithm matches these shifts as well as the rotational deviations.

This algorithm was implemented in C++ and takes less than one minute for the registration. Further speed-up of the registration process can be achieved by subsampling of the surface points extracted preoperatively. First analysis has shown that subsampling to 1/10 of the points has only negligible influence on the zone of convergence and on the final precision of the registration.

Figure 4: 3-dimensional visualization of the registration result. The bone surface is overlaid the ultrasound volume data.

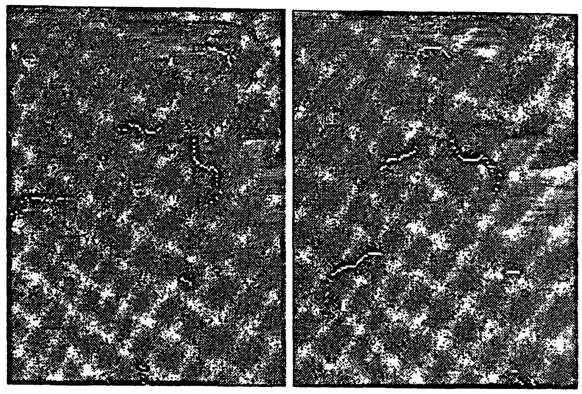

Figure 5: Surface points, extracted from the CT-data, projected into the ultrasound data. The left image shows this before registration with a rotational deviation of about 30 degree, the right image is after registration.

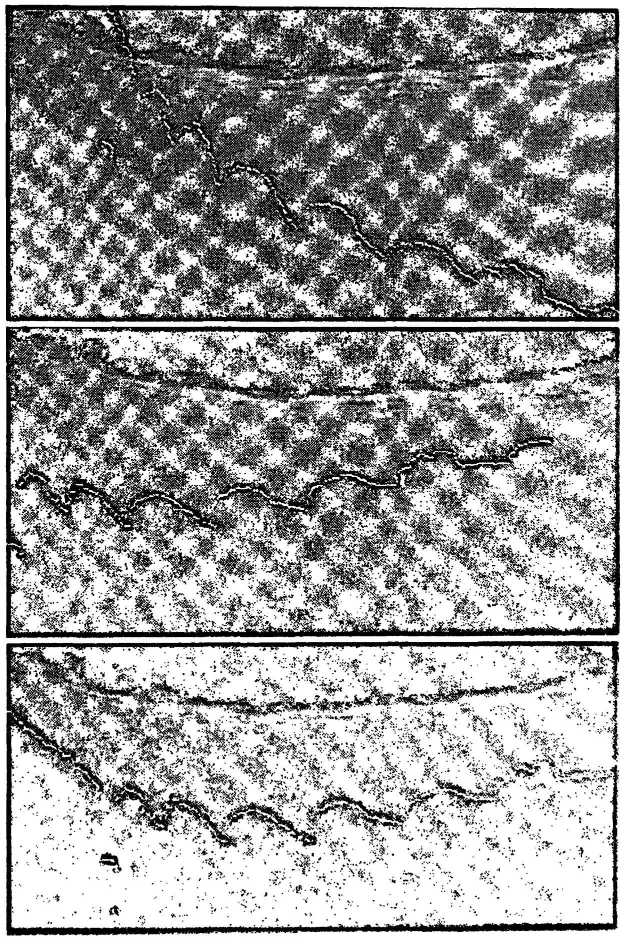

Figure 6: Surface points, extracted from the CT-data, projected into the ultrasound data. The upper and middle images show this before registration, the surface was rotated about 30 degree, and shifted 40 mm, the lower image is after registration

Discussion

We propose an algorithm to register bone structures using preoperative CT image datasets and intraoperative ultrasound. The algorithm takes into account the properties of ultrasound imaging like reflection and speckle. Also the algorithm is formulated to reach low intraoperative computation time. All time consuming preprocessing steps are done on the preoperative CT dataset. First performance evaluations have shown that this approach has the potentatial for a robust interoperative real-time registration.

Acknowledgements

This work is an activity of the Kompetenzzentrum Medizintechnik Ruhr, KMR (Ruhr Center of Competence for Medical Engineering) Bochum. It is supported by the Bundesministerium für Bildung und Forschung (German Federal Ministry of Education and Research, Az.13N8079) and Siemens Medical Solutions, Siemens AG.

References

[1] Gunkel AR, Thumfahrt WF, Freysinger W, "Computerunterstützte 3D-Navigationssysteme", *HNO*, Springer-Verlag, 48:75-90, 2000

[2] Lavallee S. "Registration for Computer-Integrated Surgery: Methodology, State of the Art". In Taylor RH, Lavallee S, Burdea GC, Mösges R, editors: Computer-Integrated Surgery: Technology and Clinical Applications. Cambridge, MA: *MIT Press*, pp. 77-97, 1995

[3] Maintz JBA, Viergever MA. "A survey of medical image registration". *Medical Image Analysis*, 1: pp. 1-36, 1998

[4] Maurer CR, Fitzpatrick JM. "A review of medical image registration". *In Interactive Imageguided Neurosurgery*, (Maciunas RJ, eds.) Park Ridge, IL: American Association of Neurological Surgeons, pp. 17-44, 1993

[5] Maurer CR, Fitzpatrick JM, Galloway RL, Wang MY, Maciunas RJ, Allen GS. "The accuracy of imageguided neurosurgery using implantable fiducial markers". In *Computer assisted radiology* (Lemke HU, Inamura K, Jaffe CC, Vannier MW, eds) Berlin: Springer-Verlag, pp. 1197-1202, 1995

[6] Fitzpatrick J, West JB, Maurer CR. "Predicting Error in Rigid-Body Point-Based Registration". *IEEE Trans on Medical Imaging*, 5:694-702, 1999

[7] Gering D, Nabavi A, Kikinis R, Grimson WEL, Hata N, Everett P, Jolesz F, Wells W. "An Integrated Visualization System for Surgical Planning and Guidance using Image Fusion and Interventional Imaging". *Medical Image Computing and Computer-Assisted Intervention*, pp. 809-819, 1999

[8] Zonneveld FW. "Intra-operative CT: implementation of the Tomoscan M". *Medicamundi*, 1:6-11, 1998

[9] Audette MA, Ferrie FP, Peters TM. "An Algorithmic Overview of Surface Registration Techniques for Medical Imaging". *Medical Image Analysis,* 3:201-17, 2000

[10] Carrat L; Tonetti J; Merloz P; Troccaz J. "Percutaneous computer assisted iliosacral screwing: clinical validation". *Medical Image Computing and Computer-Assisted Intervention*, 1229-1237, 2000

[11] Maurer CR, Gaston RP, Hill DLG, Gleeson MJ, Taylor MG, Fenlon MR, Edwards PJ, Hawkes DJ. "AcouStick: a tracked A-mode ultrasonography system for registration in image-guided surgery". *Medical Image Computing and Computer-Assisted Intervention*, pp. 953-962, 1999

[12] Muratore DM, Dawant BM, Galloway RL. "Vertebral surface extraction from ultrasound images for technology-guided therapy". *Medical Imaging*, pp. 1499-510, 1999

[13] Amin DV, Kanade T, DiGioia AM, Jaramaz B, Nikou C, LaBarca RS. "Ultrasound based registration of the pelvic bone surface for surgical navigation". *CAOS*, pp. 36, 2001

[14] Kowal J, Amstutz CA, Nolte LP. "On B-mode ultrasound based registration for computer assisted orthopaedic surgery". *CAOS*, pp 35, 2001

[15] Leotta DF, Detmer PR, Gilja OH, Jong JM, Martin RW, Primozich JF, Beach KW, Strandness DE. "Three-dimensional ultrasound imaging using multiple magnetic tracking systems and miniature magnetic sensors". *Proc. IEEE Ultrasonics Symposium,* pp. 1415-1418, 1995

[16] Prager RW, Rohling RN, Gee AH, Bermann L. "Rapid Calibration for 3D Freehand Ultrasound". *Ultrasound in Medicine and Biology*, 6: 855-869, 1998

[17] Muratore D, Galloway RL. "Beam Calibration without a Phantom for Creating a 3D Freehand Ultrasound System". *Ultrasound in Medicine and Biology,* 11: pp. 1557-1566, 2001

[18] Angelsen BAJ. *Ultrasound Imaging*. Norway: Emantec; 2000.

[19] Sugano N, Sasama T, Nakajiama Y, Sato Y, Nishii T, Iida T, Nakagawa K, Ono K, Nishii T, Nishihara S, Tamura S, Yonenubu K, Ochi T. "Effects of CT threshold value to make a surface bone model on accuracy of shape-based registration in a CT-based navigation system for hip surgery". *CARS Proc.*, pp. 306-311, 2001

[20] Hansen N, Ostermeier A, "Completely Derandomized Self-Adaptation in Evolution Strategies". *Evolutionary Computation*, 9(2), pp. 159-195, 2001