Project 20: Enhancement of US-CT registration accuracy for spinal surgery

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Paper review: Registration of 3D CT and Ultrasound Datasets of the spine using Bone Structures.

B. Brendel, S. Winter, A. Rick, M. Stockheim, H. Ernert. Computer Aided Surgery, vol 7, no 3, pp. 146-155,2002

<u>Summary of the article:</u>

In navigated orthopedic surgery, accurate registration of bones is of major interest. Usually, this registration is performed using landmarks positioned directly on the bone surface. These landmarks must be exposed during surgery. Our goal is to avoid the exposure of bone surface for the sole purpose of registration by using an intraoperative ultrasound device that can localize the bone through tissue. The authors propose an algorithm for the registration of CT and ultrasound datasets that takes into account the fact that ultrasound produces very noisy images (speckle) and shows only parts of the bone surface. This part is made from the CT dataset. Later, a surface volume registration is performed by searching for a position of the estimated surface that maximizes the average gray value of the voxels in the ultrasound dataset covered by the surface. The results showed a validation of the algorithm in validated using an ex vivo preparation of a human lumbar spine with surrounding muscle tissue. On the basis of this data, the method has a large radius of convergence and a repeatability of 0.5 mm for displacement and 0.5 degrees for rotation. Finally, the authors conclude that the proposed algorithm is robust for 3D CT and ultrasound datasets. Likewise, they report that computation time seems sufficiently short to permit intraoperative use.

<u>Resons for chosing this article</u>

- Present a clinical framework of spine samples registration that could aid understand the state of art in the field of US/CT registration
- Uses conventional volumetric ultrasound images which can be translated to simple 2D images
- Takes into consideration the bone structure for registration, which is important since the registration procedure is specially suited for this kind of tissue, potentially enhancing the robustness in comparison with general US/CT registration techniques

In general, the authors states that it is crucial to avoid the use of landmarks positioned directly to bone structure by using bone through CT/ 3D ultrasound intensity-based registration: maximizing the average gray value of the voxel in the ultrasound dataset covered by the surface. Additionally, the authors provide the following contributions to the field:

1. Very low registration error/displacement (0.5 mm)
2. Robust registration that is low sensitive to rotation
3. Simple algorithm for intensity-based registration

Technical Approach: General view

The overall diagram of the framework is presented below. Initially, the authors acquired preoperative information localized in CT volumetric 3D data, which was processed for extracting a simulated surface where the acoustic reflection will be encountered (detail of such simulations are presented later). Then, intraoperative information from volumetric 3D US data using a conventional convex array is performed over an ex-vivo human vertebra sample. The data was resampled so it has the same voxel size as the CT preoperative data. Then, the segmented US surface obtained from CT volumes is iterated over a proposed intensity-based technique that search for the maximum intensity sum over the whole US volume. Eventually, the algorithm converge to a local maxima and give the output set of angle values plus a translation vector that is later used to overlap the registered volumes. For robustness evaluation, the same algorithm was repeated with initial misalignment in angles and displacement in less than 1cm length

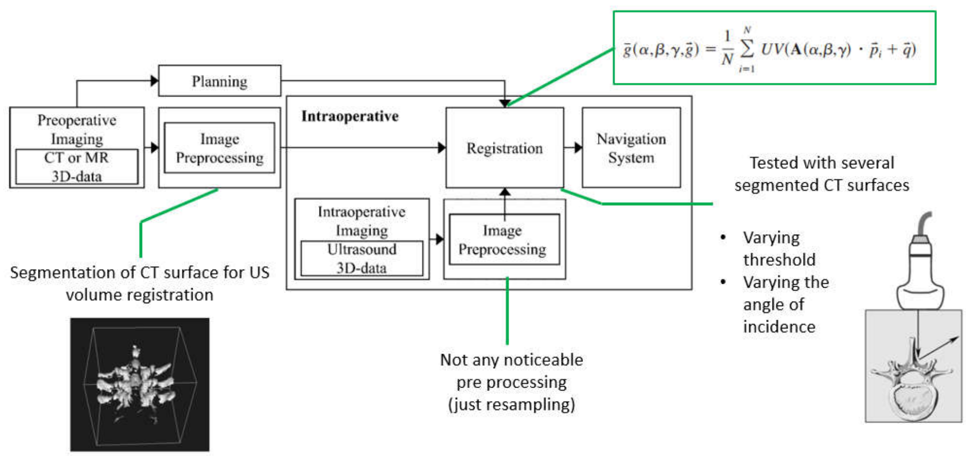

Figure 1. Overall scheme of the CT/US registration

Technical Approach: Segmenting the US surface from the CT volumes

Fig 2. Depicts some example of the segmentation of the US surface from the CT volumes. The authors take into consideration the angle of incidence of the acoustic waves that are scattered outside the field of view of the ultrasound. Hence, it generates a partial surface in comparison with the CT. However, the authors don't properly describe the procedure or the mathematical algorithm to generate such surfaces.

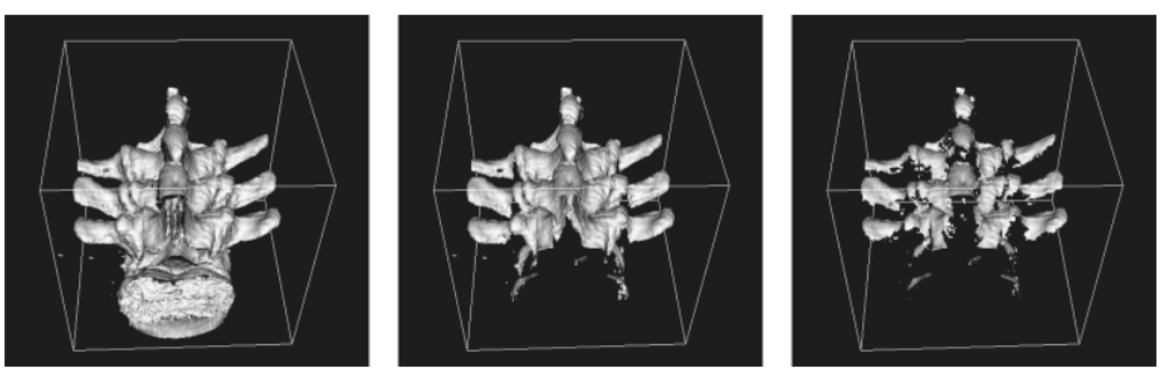

Figure 2. Generating US surface from CT volumes. Left: Original CT. Middle: Surface reached by the ultrasound. Right: Surface reached by the ultrasound after considering the angle of incidence

Technical Approach: Registration

Fig 3 depicts the cost function to maximize and the registration results of single vertebra and complete spine. While they explain correctly the value that has to be maximized in the function (i.e. maximum intensity) it is still not clear how the authors found the optimizer and metric to properly converge the function presented below. This is mainly because a translation into pixel positions cannot be differentiable for LaGrange or other gradient operations. Furthermore, a complete brute force implementation will still fail to converge since it is still sensitive to local maxima instead of global maxima

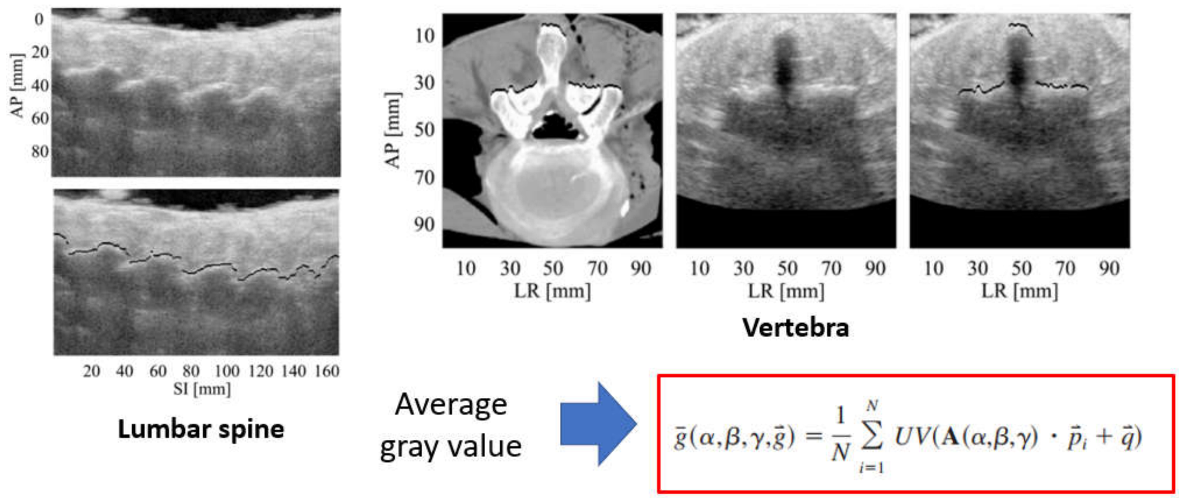

Figure 2. Registration method to correlate segmented CT surface with US volume. Left: results with the complete ex-vivo spine. Right: Registration result with a single vertebra. Bottom, equation for the intensity based registration

Registration results: varying threshold segmentation for CT and incidence angle

Additional results of the registration performance are presented below. In general, not very significant registration error was reported while changing the translational and rotational misalignment, whether the incidence angle or the intensity threshold was changed. The results suggest that the proposed algorithm is indeed robust for this misalignment range.

Table 1. Deviation of the Registration Results Depending on the Threshold for the Bone Surface Extraction in the CT Dataset

Threshold	Maximal rotational misalignment (whole spine)	Maximal translational misalignment (whole spine)	Maximal rotational misalignment (single vertebra)	Maximal translational misalignment (single vertebra)
100 HU	0.250°	0.5 mm	0.250°	0.5 mm
200 HU*	0.000°	0.0 mm	0.000°	0.0 mm
300 HU	0.500°	0.5 mm	0.125°	0.5 mm
400 HU	0.375°	0.5 mm	0.625°	0.5 mm

* Reference registration.

Table 2. Deviation of the Registration Results Depending on an Alteration of the Assumed Incidence Angle for the Ultrasound Wave

Alteration of the incidence angle	Maximal rotational misalignment (whole spine)	Maximal translational misalignment (whole spine)	Maximal rotational misalignment (single vertebra)	Maximal translational misalignment (single vertebra)
2°	0.250°	0.5 mm	0.375°	0.5 mm
4°	0.125°	0.5 mm	0.375°	0.5 mm
6°	0.125°	0.5 mm	0.375°	0.5 mm
8°	0.125°	0.5 mm	0.125°	0.5 mm
10°	0.125°	0.5 mm	0.250°	0.5 mm
12°	0.750°	1.5 mm	0.125°	1.0 mm
14°	0.625°	1.5 mm	0.250°	1.0 mm
16°	0.500°	1.5 mm	0.250°	1.0 mm
18°	0.750°	1.5 mm	0.750°	1.5 mm
20°	1.000°	2.0 mm	0.500°	1.5 mm

Good points of the article

- Fast registration: Reported 5 to 10 seconds of registration per vertebra and 50 to 100 seconds for the whole spine
- Low sensitivity in variation of CT registration (around 0.5 mm)
- Mention a curvilinear array and a specific frequency that serves as background imaging parameters for scanning the spine
- Presents a simple fixed registration that is easy to compute

Bad points of the article

- Does not specify the computation time for resampling processes.
- Does not describe the mathematical procedure to segment the CT volume taking into consideration the angle of incident
- Presents a different pattern in the ultrasound for ex-vivo spine sample with soft tissue (acoustic shadow) than a sample with only hard tissue (acoustic echo).
- Does not specify the dynamic range of the whole CT intensity in order to analyze the errors due to different thresholds.

Conclusion – Usefulness to the project

- Segmentation/Registration procedure can be conducted without filtering the US image with Fuzzy C-means segmentation

- It demonstrates the feasibility of registering only part of the CT images that can be reached by the ultrasound

- A wide patter of high intensity could lead to higher registration errors, which can be still corrected with SLSC and robust SLSC.