Advanced Computer-Integrated Surgery (EN.601.656.01.SP18) Plan propostal : Enhancement of US-CT registration accuracy for spinal surgery

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1 Background and Challenge

In conventional surgery, there is a crucial need to accurately deliver preoperative information in an intra-operative situation. While existing technologies feature sophisticated system for needle tracking and surgical tool recognition, the physician still require to know if the overall operative region is correctly defined and located.

In medical imaging, Ultrasound (US) is an imaging modality that characterizes for using non-ionizing energy and with a relatively low cost in purchasing and maintenance in comparison with computer tomography (CT) and magnetic resonance imaging. Additionally, it is a suitable technique for intraoperative scanning of the human body due to the portable characteristic of the system (freehand probe in comparison with large systems that occupies the whole surgery room) and its simplicity to use (i.e. no extended training is required for a physitian to understand the imaging technique).

However, US is commonly affected with clutter artifacts and other reflections from tissues with high acoustic impedance. Therefore, compared to the other techniques, it usually feature low Signal-to-noise ration (SNR). For instance, in a region that is ideally anechoic (no reflections and therefore pitch black region), we can sometimes see brightness inside that region due to the reflections in the surrounding tisue. Moreover, in order to have good coupling with the surface (i.e. skin), physicians often apply a certain pressure along the normal axis of the tissue, which traduces in a certain degree of deformation. Hence, there isn't a rigid relationship between intraoperative information and preoperative information (i.e. CT)

In the past 10 years, there has been scarce investigation issuing US/CT registration. Between the most used approach, intensity-based registration has been used for registering US images with MRI applied in the brain, and US images with CT applied in the kidney. Other approaches rely on feature extraction (commonly edges recognition) with the use of sobel gradient and other techiques (see Fig. 1). Lastly, there has been few studies that explore the performance of the combination of the two aforementioned techinques, which are called multi-component similarity measurements.

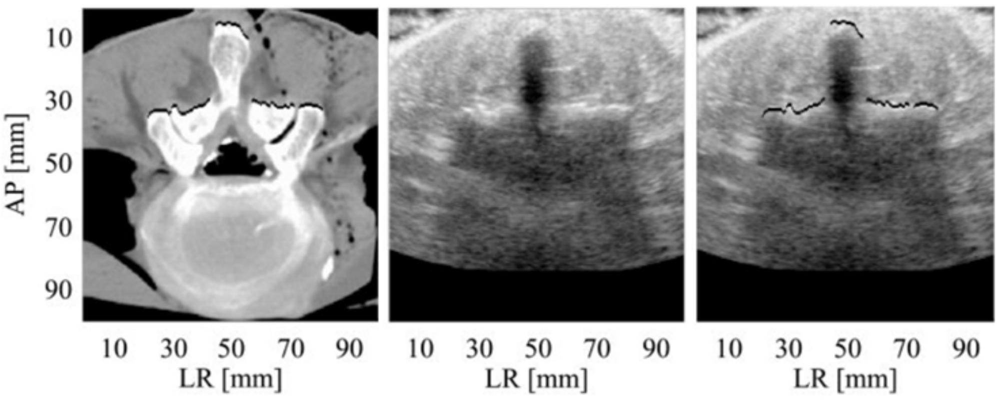

Figure 1: Registration of US/CT images of the human spine through feature extraction approaches. Brendel et. al 2002

2 Solution: Enhanced US images

In the recent advances of ultrasound imaging, several beamforming techniques has been proposed in order to enhance the queality of the reconstructed images. One of them is Short Lag Spatial Coherence beamforming (SLSC), which takes into consideration the coherence between the acquired channel data in order to reduce clutter and thus, increase contrast. This technique is different from conventional ultrasound techniques since it does not provide a map of brightess (acoustic impendance) but the coherence between near regions.

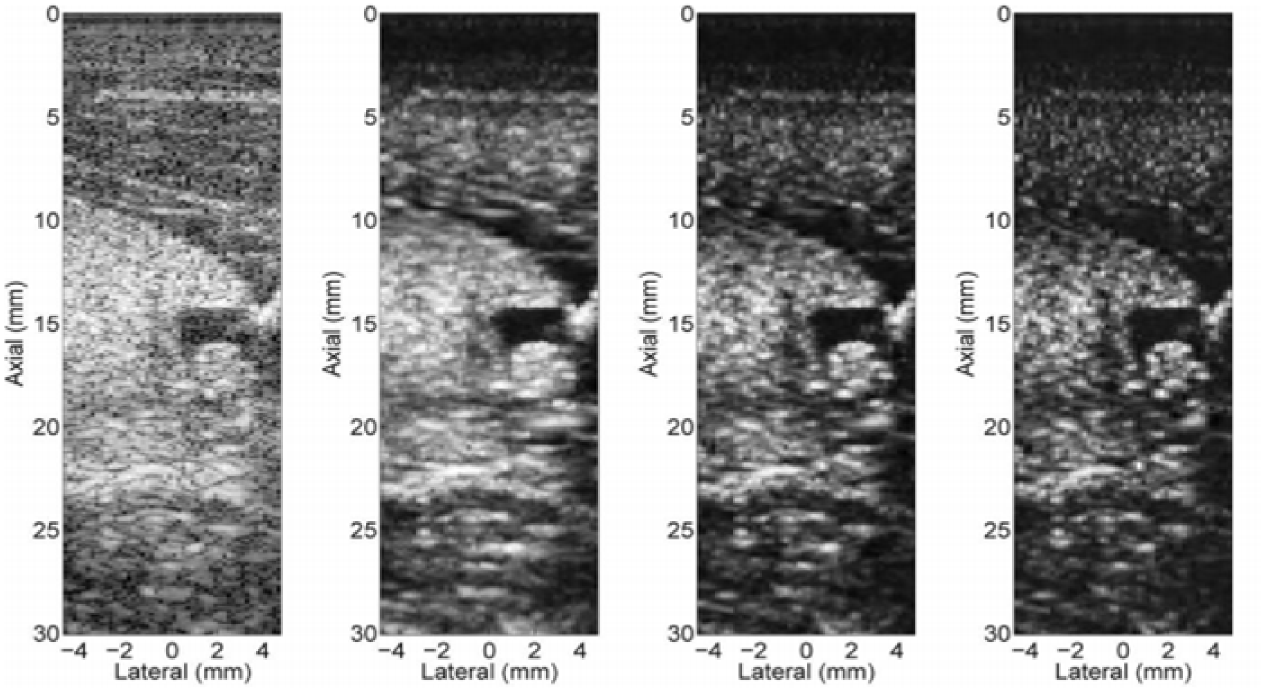

Figure 2: Comparison of a US image of the human tyroid (left side) with several SLSC images (varying the cummulative summed lag M). Lediju et. al 2011

As observed in Fig. 2, SLSC can potentially increase the contrast (with the tradeoff of resolution) by adjusting the quality parameter M, which is the cummulative summed lag. By doing this, it will benefit the performance of feature extraction and/or intensity-based techniques for CT/US registration. It is also worth mentioning that this improvement can potentially benefit neddle tracking from US images analysis, since the contrast of the needle and the surrounding tissue will be likewise enhanced.

3 Objective

The objective of the proposed project is to explore methods to improve accuracy of US-CT image registration through improved US image resolution. As specific aims there is:

- Enhance bony features in US images to improve resolution for automatic registration
- Develop a robust beamformer to improve the appearance of bone in US images
- Explore registration improvement when considering additional information from Photoacoustic (PA) images

4 Technical Approach

Conventional ultrasound imaging usually relies on delay and sum (DAS) techniques that are presented in the equations below, where dynamic receive beamforming is computed with respect to a focus point in the axial dimension that varies for each pixel depth:

$$\tau(x_1, x, z) = \left(z + \sqrt{z^2 + (x - x_1)^2}\right)/c, \qquad s(x, z) = \int_{x-a}^{x+a} RF\left(x_1, \tau(x_1, x, z)\right) dx_1.$$

Figure 3: Conventional Delay and Sum for generating A-lines with acquired channel data

where a is half the aperture, (x,z) is the current pixel point to be reconstructed and x1 is the position of the element 1 in the aperture. On the other hand, SLSC beamforming takes into consideration the coherence or correlation factor between adjacent radiofrequency signals separated over a certaing lag m. Then, it sum all the lags of an specific signal to depicts the total coherence along a surronding kernel which is commonly in the order of few wavelenghts (controled by the transmit frequency and the sound speed of the medium):

$$\hat{R}(m) = \frac{1}{N-m} \sum_{i=1}^{N-m} \frac{\sum_{n=n_1}^{n_2} s_i(n) s_{i+m}(n)}{\sqrt{\sum_{n=n_1}^{n_2} s_i^2(n) \sum_{n=n_1}^{n_2} s_{i+m}^2(n)}} \qquad R_{\mathrm{sl}} = \int_1^M \hat{R}(m) \mathrm{d}m \approx \sum_{m=1}^{M} \hat{R}(m).$$

Figure 4: Original Short lag spatial coherence algorithm using the acquired channel data (complex)

Since this is an explorative study of CT/US registration, we will focus on the bone structure of the spine. Therefore, we will be using samples with mostly hard tissue (only bone). For the US acquisition, the spine specimen will be submerged in tank of ionized water where the ultrasound will be placed at the top and holded by a ring stand. The transducer to be used will be either a linear array or a phased array, depending on the depth of the region of interest (ROI) that we want to analyze. For the CT acquisition, no special considerations are needed.

Once the data is collected and reconstructed, the image will be enhanced by feature extraction of the bone using Fuzzy C-means segmentation. Three clusters will be specified for the segmentation: bone (desired region which is represented as high intensity in the image), water (ideally dark regions but it has undesired reflections), and regions outside imaging boundaries (which is the case for phased arrays since the image is not entirely rectangular). An example of the feature extraction in the nose region of a human skull using Fuzzy C-means is presented below:

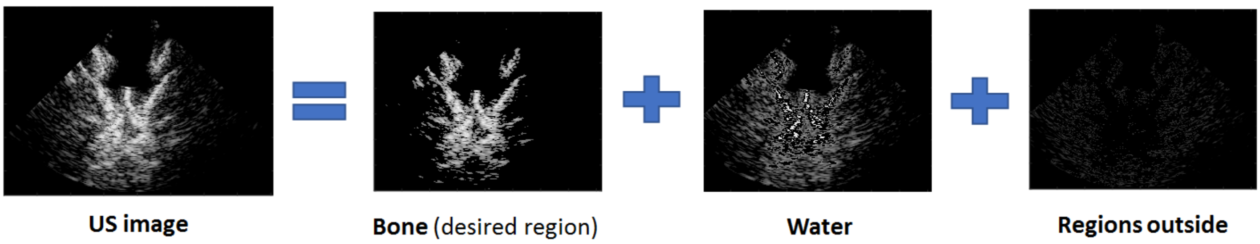

Figure 5: Feature extraction with Fuzzy C means segmentation

The selected mask (bone region) is then set as input for rigid registration with CT images using Mates Mutual Information. However, depending on the registration performance other registration methods can be evaluated as well, such as Iterative Cloud Point registration (ICP). The performance measurement will be computed with standard metrics, such as the mean square error of the overlapped structures (MSE).

Finally, the registration pipeline will be repeated while varying the quality of the US images. The quality parameters for DAS, SLSC and Robust SLSC images will be the dynamic range, cummulative summed lag and regularization parameter, respectively.

5 Work plan

The proposed work plan is presented below

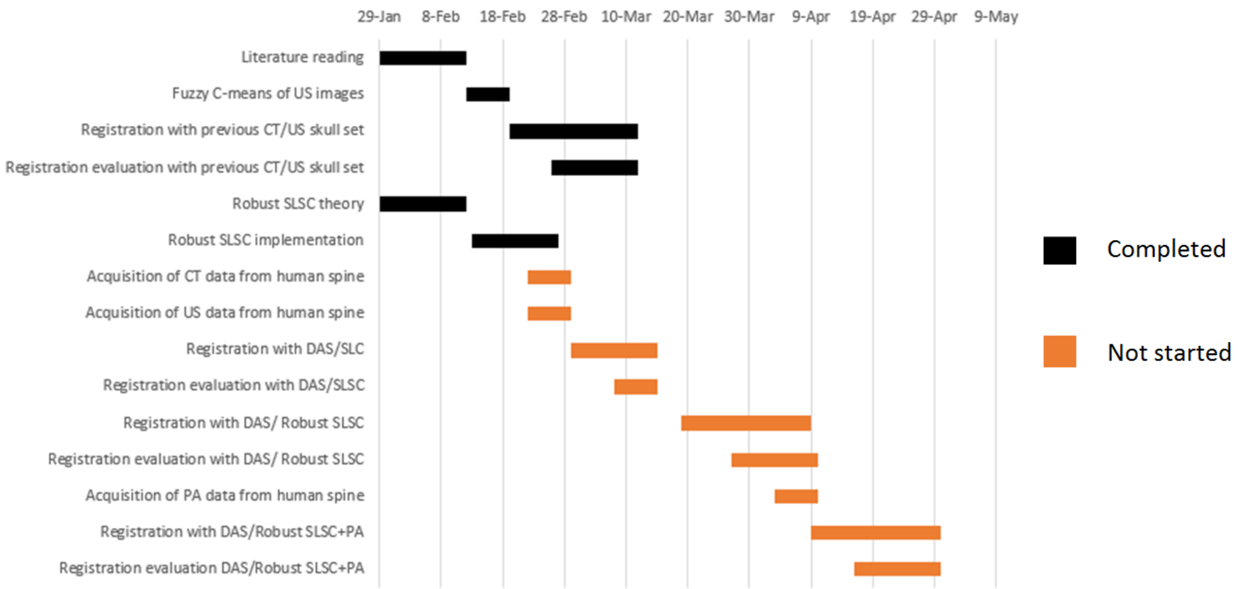

Figure 6: Proposed work plan

6 Deliverables

The specified deliverables are presented below

Table 1: Deliverables

Type	Minimum (March 8th)	Expected (April 5th)	Maximum (April 19th)
Images	Automatic registration of SLSC/DAS US images to CT images of spine specimen (hard tissue)	Add robust SLSC to registration framework	Add PA to registration framework
Equation	Propose algorithm for a robust SLSC technique	No additional equations	No additional equations
Graphs	Show registration performance when varying quality parameters for SLSC and DAS	Add quality parameters for robust SLSC (e.g., kernel size and regularization parameters)	Compare CT-PA and CT-US registration performance using PA images

7 Dependencies

Since our lab is not in possession of our own CT system, acquisition of CT data is a dependency from other labs disposition. The CT acquisition can be conducted in either the medical campus under the coordination of Professor Siewerdsen and his postdoctoral student or the Homewood campus under the coordination of colleague Michell Graham and the CAMP lab members. The difference between the two CT system is mainly the enhanced resolution from the one located in the medical campus. However, since the US image has considerably less spatial resolution than conventional CT image, high resolution CT images are not required.
In order to validate the registration techniques, a calibration phantom (commonly a wire phantom) will be tested for such purposes. This phantom is currently being designed by one of the members in our lab (Master student). Finally, since the aforementioned sample is currently shared with other project (Blackberrie Eddins), a scheduling for imaging acquisition will be conducted.

8 Bibliography

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