Improved Minimal-Invasive Laparoscopic Liver Surgery by Registration of 3D CT and 2D Ultrasound Slices

S. Heldmann[1], B. Beuthien[2], J. Olesch[2], and N. Papenberg[1], B. Fischer[1,2]

[1]Fraunhofer MEVIS, Projectgroup Image Registration, Lübeck, Germany
[2]Institute of Mathematics and Image Computing, University of Lübeck, Germany

stefan.heldmann@mevis.fraunhofer.de

Kurzfassung

Die Arbeit beschreibt einen neuen Ansatz zur Registrierung von dreidimensionalen CT-Daten mit im Raum aufgenommenen zweidimensionalen Ultraschallschichten, deren Lage durch ein Trackingsystem beschrieben wird. Derartige Probleme sind für die navigierte Chirurgie relevant. Eine Schwierigkeit besteht in der nicht vollständigen Abdeckung des Raumes durch die Ultraschallschichten. Bisherige Ansätze nutzen sogenannte Compounding-Techniken, um zwischen den Ultraschallschichten künstlich Daten zu erzeugen. Der neue Ansatz hingegen schafft eine Möglichkeit, die unterschiedlichen Daten nur an den Positionen der zweidimensionalen Schichten zu vergleichen. Das resultierende Verfahren nutzt Gauß-Newton-Techniken zur Optimierung und eine Multi-Level Strategie zur Beschleunigung. In der Arbeit werden neben dem Verfahren erste Ergebnisse präsentiert und ein Ausblick auf weitere Forschungsmöglichkeiten gegeben.

Abstract

In this work we present a new approach for image registration of 3D images and scattered 2D slices. Our work is motivated by the FUSION project on minimal invasive navigated laparoscopic liver surgery. Therefore, we need to register volumetric computer tomography (CT) data and tracked ultrasound (US) slices. One particular problem is that the set of all US slices does not assemble a full 3D domain. Other approaches use so-called compounding techniques to interpolate a 3D volume from the scattered slices. Here, instead of inventing new interpolated data, we directly work on the given US slices and compare the images at the location of the 2D slice data in 3-space. The upcoming registration algorithm makes use of a Gauss-Newton scheme embedded into a multi-level framework. The paper closes with promising results and an outlook on further steps.

1 Introduction

Tumors in liver belong to the five most common malignancies worldwide. Besides other treatments, such as radio frequency ablation for small lesions, the only known curative therapy is surgical resection. Such an intervention precedes an involved pre-operative planning. Therefore, typically 3–5 days before an intervention, an abdominal CT of the patient is taken to create an individual planning by means of segmenting vessels and liver segments and subsequently by defining intersection lines and risk calculation. During intervention the surgeon is guided by tracked ultrasound (US) images of the liver. To fully exploit the pre-operative planning the CT data has to be aligned to the actual deformation of the liver given by the US data [1]. In this work we present a method for rigid alignment of pre-operative CT data and intra-operative tracked ultrasound by a novel image registration technique. Our work is part of the FUSION project (FUture Environment for Gentle Liver Surgery Using Image-Guided Planning and Intra-Operative Navigation).

A particular challenge here is that we are focusing on laparoscopic liver surgery. Due to technical restrictions in navigated laparoscopic surgery the US data is recorded as a sequence of two-dimensional slices in 3-space in contrast to volumetric 3D CT data. Figure 1 illustrates the setting. In a first approach, one might try to use standard volumetric image registration algorithms in combination with so-called compounding of scattered 2D US slices where a volume is interpolated from the slice data. This approach has several drawbacks and problems [2,3,4]. In addition to algorithmic shortcomings, matching volumetric CT data to artificially generated volumetric US data does not provide confidence in registration results for the surgeon.

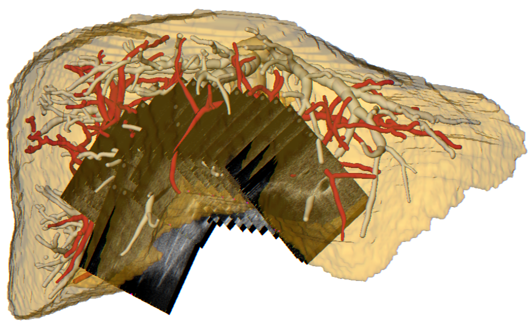

Figure 1 Setting of the registration problem. The tracked US slices are shown together with the vascular system and surface of the liver.

2 Method

The approach taken here is different. Rather than inventing the missing 3D data, we follow the approach proposed in [5,6] by computing a rigid deformation based on matching the 3D data restricted to the known locations of the 2D scattered slices. Practically that means we compute a deformation of the 3D volume, evaluate the deformed image at the positions of the 2D slices and compare it to the given ultrasound data. Then we repeat this procedure until we found a deformation that produces a satisfactory alignment of the slices. Mathematically, we formulate this as an optimization problem where we minimize a suitable customized cost function. To this end, assume we are given n ultrasound slices $S^{(k)}$ $(k=1,2,\ldots,n)$ where each slice consist of $m_1 \times m_2$ pixels $S_{ij}^{(k)}$ $(i=1,2,\ldots,m_1$ and $j=1,2,\ldots,m_2)$ that are located at points $x_{ij}^{(k)}$ in 3-space. Furthermore, assume T is the given CT volume and let $T(x_{ij}^{(k)})$ be the CT volume evaluated a point $x_{ij}^{(k)}$ by the US slices. Thus, we are in position to relate the ultrasound pixels $S_{ij}^{(k)}$ to the corresponding intensities of the CT volume $T(x_{ij}^{(k)})$. Clearly, ultrasound and CT are two different modalities whose intensities cannot be compared directly. In the literature one may find several distance measures, which are capable of dealing with multi-modal data for the price of a considerably increased complexity. Here, we use a simple but very efficient trick to be able to apply a mono-modal distance measure. The idea is to segment the vessel structure in both modalities and subsequently to compare the obtained binary data. For the US data this is done by some simple, standard preprocessing steps. Note, that this information is already available for the CT volume, since extracting the vessel system is already done for the generation of the planning data. Then we use this binary information as input images for the registration where we additionally apply smoothing to the binary images [7]. As a result, for the registration we are able to use the popular sum-of-squared differences distance measure (SSD) for comparing an ultrasound slice $S^{(k)}$ with the corresponding slice of the CT data $T(x^{(k)})$. Summarizing, we compute a rigid deformation Q by minimizing following cost-function:

$$D(Q) := \sum_k \sum_{ij} \left(T(Qx_{ij}^{(k)}) - S_{ij}^{(k)} \right)^2 = \sum_k \mathrm{SSD}^{2D}(T(Qx^{(k)}), S^{(k)})$$

For the minimization we employ a Gauss-Newton method embedded into a multi-level scheme as proposed in [7].

3 Results

To show the capability of the outlined method we perform rigid volume to slice registration on real clinical data as shown in Figure 1. The data consists of 278 US slices of size 430 x 300 and a CT volume of size 447 x 299 x 174. The implementation is done in Matlab whereas the visualization is realized in MeVisLab. All computations were carried out on a Mac with two 2.8 GHz Quad-Core Intel Xeon processors and 32 GB RAM. The multi-level scheme was applied with eight levels, resulting in a overall computation time of about 120s. To judge the performance of the scheme, we present in Figure 2 and 3 the registration result for just a single slice, though the computation was carried out for all slices. Even for a non-expert, the stunning performance of the new approach is clearly visible. In addition, the obtained results were inspected by an expert, underscoring the very satisfactory results.

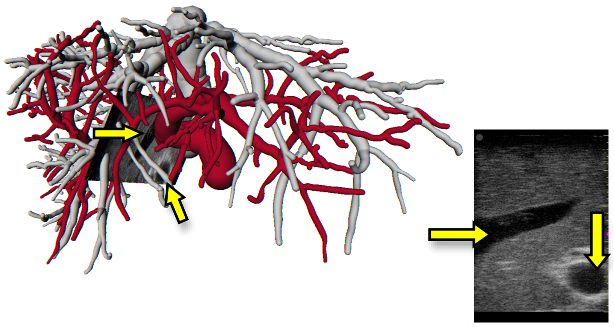

Figure 2 Left image: vascular system of the CT overlaid with a single US slice before the registration. The interesting vessels are highlighted. Right image: single US slice.

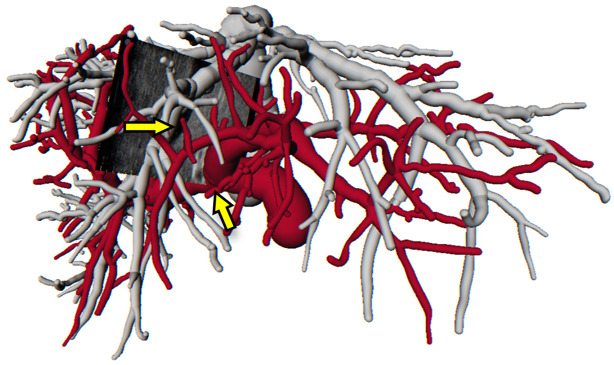

Figure 3 Vascular system of the CT overlaid with a single US slice after the registration.

4 Discussion

We have presented a novel approach for rigid registration of pre-operative volumetric CT data and intra-operative acquired 2D US scans. Our first results show that the method is generally able to successfully compute a reasonable rigid alignment of the preoperative planning model to the intra-operative situs. However, an important point is that we still rely on a fair initial guess that is we need a reasonable calibration of the tracking system in order to be able to start the scheme already in the target region. This is essential, since the ultrasound data covers only a small part of the whole liver and therefore the preoperative planning model.

To conclude, our method seems to produce results significantly superior to existing approaches based on compounding. Furthermore we are working on a clever thinning of the US data that leads to big savings in terms of computational time, which will be even more pronounced in a proper C-implementation.

Besides further testing and refinement of our method, future work includes non-rigid registration techniques. Clearly, liver is an elastic tissue and rigid registration is not able to cover complex deformations as they typical occur in practice. However, the success of any non-rigid scheme does heavily rely on a good starting point, which now is on our hands. That is, based on the promising rigid registration result we aim to perform subsequent elastic registration for final alignment of pre-operative planning and situs.

5 Literatur

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