High-Quality 3D Visualization of In-Situ Ultrasonography

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Abstract

In recent years medical ultrasound has experienced a rapid development in the quality of real-time 3D ultrasound (US) imaging. The image quality of the 3D volume that was previously possible to achieve within the range of a few seconds, is now possible in a fraction of a second. This technological advance offers entirely new opportunities for the use of US in the clinic. In our project, we investigate how real-time 3D US can be combined with high-performance processing of today's graphics hardware to allow for high-quality 3D visualization and precise navigation during the examination.

1 Introduction

Ultrasound imaging and visualization is frequently used for diagnostic purposes. There has been a rapid development of hardware solutions, signal processing, and clinical methodology related to medical ultrasound (US). The currently available 3D visualization methods for US are, due to presence of noise and other visual artifacts, unsatisfactory. Ultrasound is also used as a guide in minimally invasive procedures. Instead of visual confirmation the physician uses the US images to navigate and confirm the position of the instruments in relation to the treated area and important anatomical structures. Therefore, it is very important that the guidance is precise, otherwise it may cause significant complications for the patient. Ultrasound-assisted navigation is used frequently for neurosurgical and cardiac interventions. In both cases, the precision of the navigation is secured, either by external optical tracking mounted on the patient's cranium, or by the fact that the organ, in the latter case the heart, fits entirely into the US scanning sector for the whole heart cycle.

The situation is different for gastroenterological interventions [ØGG05], where none of these two conditions are fulfilled. The soft tissue in the abdomen is constantly moving, mainly due to respiration or pulsation from large vessels. The currently available US technology supports tracking based on an external magnetic field. Such a system, even if it is well calibrated, does not warrant proper positioning for guidance. After slight patient's movement, breathing, or displacement of the magnetic antenna, such tracking gives wrong positioning information. Respiratory or ECG gating can be applied, but this will reduce the high temporal resolution, which is a great advantage with diagnostic US. In such a case, there is a need for an internal positioning technology.

The lack of meaningful 3D visualization and of precise navigation, are both characteristics of current examinations The liver, i.e., the largest internal organ in the human body, is object of several interventions such as liver lobe resection, biopsies, or various tumor ablation techniques. For these procedures, US is used as a guiding modality either before or during the procedure. Since a precise and informative guiding visualization is lacking, several compromises are made. One such compromise is to request the patient to pause breathing in a specific phase of respiration (e.g. after maximal inspiration), and then perform the intervention during this pause. Sometimes, the breathold is needed for the sake of intervention safety itself, but in other cases only for registration purposes. This unnecessarily slows down and complicates the entire procedure. Another limitation is that clinicians spend significant time when reconstructing 3D information from slicing. A third limitation is the refusal of 3D visualization in the examination, because the prominence of noise does not allow any meaningful view of the liver.

Based on frequent interdisciplinary discussions, we have developed an advanced visualization system that provides high-quality 3D visualizations of abdominal US data, with

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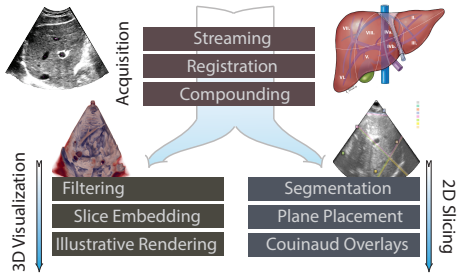

Figure 1: Workflow: The data is streamed over network for a compound-volume build-up. The 3D visualization filters the volume and presents with embedded position of current slice and illustrative rendering. The slice is enhanced with Couinaud segmentation obtained through vessel extraction and plane placement procedures. On the right the Couinaud segmenatation [Cou57] is shown. Illustration is printed with permission from ©Kari C. Toverud MS CMI.

potential for a use in diagnostic imaging and 3D navigation. As 2D US is and will remain very important for a broad spectrum of clinical cases, the presented system therefore includes a dedicated navigational overlay visualization, composited on demand over the US slice. The following sections will describe the developed system, its main components shown in Fig. 1, and demonstrate its outcome through images and accompanying video.

2 System Overview

The entire system is based on a real-time acquisition of 3D US volumes, also referred to as 4D US. We use a Vivid E9 system with a 4V-D 3D transducer (GE Vingmed Ultrasound, Norway). The data, i.e., B-mode echo amplitudes are streamed at the frame rate of approximately five volumes per second from the ultrasound device via a Gigabit network to a dedicated workstation with the latest GPU hardware (NVidia GeForce 580) that runs our prototype implementation. There, the volume is resampled to a Cartesian grid to reduce the complexity of the data processing and to anonymize confidential vendor information about the transducer design.

2.1 3D Ultrasound Visualization

In liver examinations, even the largest 3D volume probe settings cannot encompass the entire organ. Our aim is to visualize the entire organ of interest for orientation purposes in 3D and show at which particular part the currently imaged US section is positioned. Therefore, as the first step, we perform a procedure that combines several consecutive volumetric data sets and stitch them together to a larger compound volume. This is done in a process called multi-frame registration, where several volumes are co-registered simultaneously, to achieve high registration precision. The registration is based on a sum-of-squared-differences similarity measure and a simplex method for optimization as described in our earlier work [ØWU*12]. The execution is accelerated by an efficient OpenCL implementation so that the compounding process can stitch hundreds of volumes together within approximately one minute.

The registration procedure itself reduces the presence of random noise, but the structured noise (speckle, etc.) still remains in the compound volume. For 3D visualization of stitched US data, it is important that the speckle is removed, otherwise it will dominate the visualization and obscure visibility of structures in the imaged organ. To remove it, we have designed a special filter that preserves structures in the data. Instead of standard spherical-neighborhood based filtering, the new filter performs averaging along a 3D curve with the most similar intensity values. The path of the 3D curve is computed as the direction of the lowest variance of a particular voxel with respect to its value and the values of its neighbors. The filter thus aligns to important elongated structures and preserves their shape, while the less structured elements in the data set are eliminated. The filtering approach has been described in full detail earlier [SHW*12].

The filtered volume is then ready for the rendering step. Employing gradient-based techniques for shading would give prominence to remaining noise that would occlude the structure since gradient estimation via differences is a numerically sensitive operation. Therefore, integration-based illumination models are more suitable for rendering US data. For this purpose, we have developed the multi-directional occlusion shading model that extends earlier integrative illumination approaches with interactive positioning of the light source [SPBV10]. To eliminate overdarkening in the umbra region of the shadow so that the examiner is able to see all structures clearly, we propose chromatic shadows as a solution adopted from the traditional illustration [SPV11]. The pipeline of compound volume generation, filtering, and illustrative gradient-free illumination allows a clear presentation of liver vasculature, superior to previous approaches based on US. The 3D visualization is of value for the clinicians as such, and it can be combined with two-dimensional views for navigational purposes.

2.2 Guided Navigation in 2D US

Although a clear 3D visualization of US data is possible, 2D US will still be most commonly used. For 2D ultrasonography, it is important to provide good navigational support, so that the examiner receives spatial orientation assistance. One simple approach could be to offer a 2D-US view or a 3D view as described in the previous section, where the US slice position and orientation is shown in relation to the rest of the 3D structure. Its position can be obtained through real-time image-based tracking [ØWU*12], where a current position can be embedded into the compound volume. In the case of a liver examination, liver lobe partitioning is helpful for localization of lesions [SPSP02]. One such partitioning, applicable to the majority of the human population, is the

Couinaud partitioning [Cou57]. The organ is divided based on the geometry of the vascular tree in the liver as shown in Fig. 1. Currently, the clinical personnel is challenged to mentally reconstruct how the Couinaud partitioning divides the liver into lobes, often assisted by navigational posters on the wall of the examination roo, to localize focal lesions in the liver. Our aim is to enrich the US examination procedure with augmented liver partitioning to reduce the burden of spatial reconstruction for the clinician, so that he or she can concentrate on the central tasks of the examination.

The Couinaud as well as other liver-partitioning schemes are based on the geometry of the vascular anatomy. In our pipeline, we therefore adapt a segmentation technique of the hypoechoic regions, such as blood vessels, that can deliver us a basic liver vessel structure of the compound volume within a few minutes of an interactive controlled mask-growing process [PSSH06, BV10]. During the scan, the user manually adds seed-points for the region-growing algorithm. The extracted regions are visually evaluated by the user and they are added to the final segmentation mask only if they are deemed as valid segments of the vessel tree. In order to extract vessels larger than a single 3D US sector, image-based tracking is used to stitch together vessel segments from each time-step. Once the major direction of the vessel tree is determined, we place planar sheets that are aligned with the vascular structures as closely as possible. The first plane is a horizontal plane that divides the liver into an upper and a lower segment, and it is placed in the branching of the portal vein. The three remaining planes are oriented vertically and placed so that each of them slices one of the right, middle or left hepatic veins, and at the same time slices through the middle of the inferior vena cava. As the hepatic veins usually are curved, the positioning of the planes can be difficult without extensive anatomical knowledge and if based only on US slices. With a segmented vessel tree, however, it is easy both to place the planes and to verify the correctness of the placement by rotating the 3D model. The planar arrangement defines the partitioning of the liver parenchyma and allows for easy determination of where which structures are located. In our previous work, we have proposed several visual metaphors for Couinaud partitioning overlays [VNOy*08, ØUG*11], which we also employ in our latest setup. Unlike in the previous cases, we have dropped the magnetic tracking, because of poor precision. Instead, we employ the real-time image based tracking, where we register the current US volume with the previously obtained compound volume of the liver of the same patient. This registration then serves for linking the Couinaud partitioning of the liver into the 2D US slice.

3 Results

The presented results are the outcome of a large collaborative effort between medical visualization and clinical researchers. Our pipeline consists of building blocks, predominantly developed in our project, that have been previously published and evaluated in their own context. The entire prototype has not yet been thoroughly clinically tested, and we see clinical testing as a natural and necessary step towards clinical integration. At this stage, we demonstrate our technology on one test case, where a 27 years old healthy female volunteer with a standard liver vascular anatomy has been examined with our system.

During the data acquisition, we have used the hardware setup mentioned in Section 2. We have set the transducer scanning zone to 80 by 40 degrees, to achieve a compromise between data quality and volume second frame rate. Normally only a small portion of the liver can be scanned within the US sector. Due to the small footprint of the 4V-D US probe we used a spacer between the probe and the skin to include more of the liver in the sector. The spacer was prepared from gelatine prepared from porcine skin and we did not notice any artifacts in image quality caused by this additional piece.

The first scan in our pipeline aimed at producing a dataset that covers the entire liver. This was achieved in a long sweep sequence where both translation and rotation transformations of the transducer was used. This scan was done during breath holding and it took between 30-45 seconds. Roughly 150-200 volumes were resampled into several resolutions, a 64^3 or a 128^3 resolution was used for the purpose of multi-frame registration, while a 256^3 or a 512^3 resolution was used for the compound volume representation. The resulting compound volume had resolution of 256^3 or 512^3 voxels. The entire process did not require any user involvement, as the image-based registration is an automated process. The result is shown in Fig. 2 top left. The next step was a feature-preserving filtering for the purpose of 3D visualization, which is fully automated as well, and it was carried out within 3 to 10 sec. Fig. 2 top right shows a comparison of a visualization of the original (left half) and the filtered data (right half).

For the purpose of liver examination, a live Couinaud segmentation is a helpful navigational aid. We performed the Couinaud partitioning in a two-stage rapid process of (a) iterative vessel segmentation, and (b) space-partitioning through a plane placement. This process took in sum a little over five minutes, which is an acceptable time span. The vascular structures that have been possible to extract from the US data acquisition were the three hepatic veins and branches of the portal vein. This vascular information is sufficient for the Couinaud segmentation and the vessels, together with the plane placement shown in Fig. 2 middle.

The final step is the examination itself. Here, the examiner can take advantage of additional information obtained through our system, by co-registering each US volume within the compound volume. This process is fully interactive for sector sizes of 64^3 voxels on modern GPUs. While the registration is at the moment suffering from frame jittering, for areas free of acoustic shadows, we were able

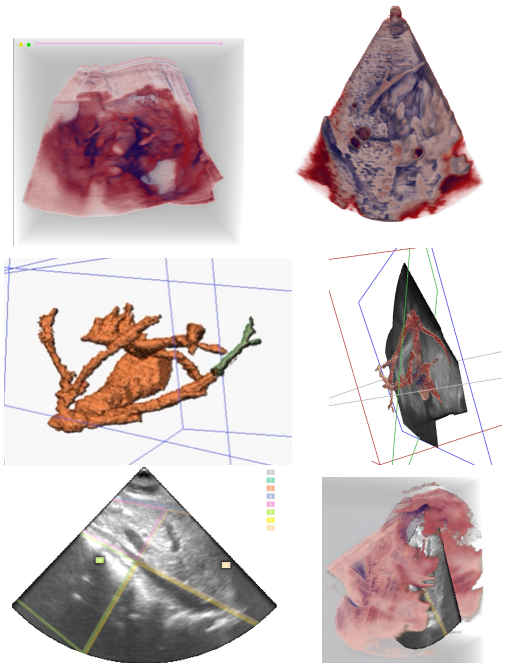

Figure 2: Results: The top row shows the result of the compounding process, and the feature-preserving filtering. The middle row shows the result of the segmentation process and the setting of the space-partitioning planes. The bottom row shows the 2D examination enhanced with a Couinaud segmentation and the embedding of a slice into a 3D rendering for aiding space orientation.

to achieve satisfactory registration results even during free breathing. This is currently not possible with any navigational aids implemented in current US systems. The operator can choose two additional visualization modes, either a 2D slice with Couinaud partitioning, or, for better navigation in 3D, the embedding of US slice in the compound volume covering the entire liver organ. These visualizations are shown in Fig. 2 bottom.

4 Clinical Relevance

The benefits of the described technology have been analyzed by our cooperating clinical experts. Below are the statements that define the relevance as seen from the clinical perspective. The compounding feature could be useful in clinical settings such as organ volume estimation, especially in cases when the organ volume is a good marker of a disease or follow-up of treatment. The compound-volume generation could enable slicing through the entire organ, and enable fusion of detected lesions from one examination to another. The compounding can also be used for the registration of time-varying data, such as contrast-enhanced US, and building a 4D perfusion dataset. The 3D visualization of the compound volume, which highlights the vessels could be useful, when vascular malformations or tumor vasculature are being examined. The registration can be useful for obtaining positional information in or around the organ. One could use the external positional systems, but those are inaccurate and cumbersome to use. The Couinaud segmentation is important for the doctor-to-doctor communication, for example between an internist and a surgeon, as it expresses anatomical landmarks, liver vasculature and other findings. Currently, the communication is aided by posters hanging in the US examination rooms to remind the examiner of the Couinaud partitioning. Implementing a computational partitioning into the scanner is desired, as it will give the operator a useful tool for communication to the best of the patient.

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