Synthetic Aperture Focusing in 3D Ultrasound Transmission Tomography

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Abstract. The paper studies ultrasound transmission tomography as an imaging modality for breast cancer diagnosis. Reconstruction of sound-speed images is presented for the Karlsruhe 3D ultrasound transmission tomograph. The problems of sparse spatial distribution of ultrasound transducers and of low signal-to-noise ratio are approached using synthetic aperture focusing. The image reconstruction is done based on regularized algebraic reconstruction. The proposed method is tested on simulated data as well as on measured phantom data.

1 Introduction

Ultrasound computed tomography (USCT) is an imaging modality intended as an alternative to X-ray and conventional ultrasound imaging in breast cancer diagnostics. The acquisition setup is similar to X-ray computed tomography (CT) [1]. The imaged object is immersed in a water tank, surrounded by ultrasound transducers, where one transducer emits ultrasound wave while other transducers receive the transmitted and reflected/scattered signals. Images of several diagnostically important parameters can be reconstructed from the received signals: reflectivity, sound-speed and attenuation. This contribution focuses on sound-speed image reconstruction.

Currently, USCT is still in the stage of research, mainly due to complexity caused by phenomena inherent to ultrasound signal propagation, such as diffraction and refraction. Most published USCT devices are constructed as 2D systems (e.g. [2]), with a ring of fairly large transducers. Our approach is based on a 3D USCT system, described in [3], where transducers are positioned on the surface of a cylindrical tank. Such transducer distribution enables fast acquisition of spatial 3D data, but it brings also several challenges, mainly sparse transducer distribution and low signal-to-noise ratio (SNR) due to small transducer size.

An approach to overcome the sparse transducer distribution and low SNR by means of synthetic-aperture focusing is presented. Example results reconstructed from synthetic data and data measured on a breast phantom are shown.

2 Methods

The problem of 3D sound-speed image reconstruction can be formulated as reconstruction from projections. Here, the projections are formed by time-of-flight (TOF) values, i.e. the ultrasound propagation times measured for each emitter-receiver combination. The sound-speed image reconstruction is solved as a 3D regularized algebraic reconstruction [4]. In contrast to the widely used filtered backprojection method, the algebraic reconstruction enables regularization of the reconstruction. Here, the regularization imposes piecewise smoothness of the resulting sound-speed map, while preserving edges (details can be found in [4]). In addition, the algebraic reconstruction approach enables incorporation of non-straight propagation paths, e.g. due to refraction (not implemented here).

The data acquisition is done in 6 steps. After each step the whole USCT system is rotated, in order to increase the number of effective transducer positions [3]. Hence, the system has 6 times more “virtual transducer positions” than the physical number of transducers. The received radiofrequency transmission signals are measured and stored for all emitter-receiver combinations within each rotation position. This allows us to use a synthetic aperture formed of nearby virtual transducer positions by appropriately delaying and summing their radiofrequency signals. The aperture size is given by the number of neighbouring transducers used for focusing.

The focusing procedure is done in two steps: first, focusing on the receiver side (delay and sum of the radiofrequency signals) is done with the focal point positioned to each emitter of the emitter aperture. Then, the resulting focused signals are focused (i.e. accordingly delayed) so that the emitter aperture is focused to the center of the receiver aperture.

As it is practically impossible to run the above described processing on a standard PC computer (a dataset consists of about 3.5 million radiofrequency signals, which needs approximately 20 GB of storage capacity), the algorithm was parallelized and implemented using Matlab® Parallel Computing Toolbox™ and Matlab® Distributed Computing Server™ in a heterogeneous computing cluster environment.

3 Results

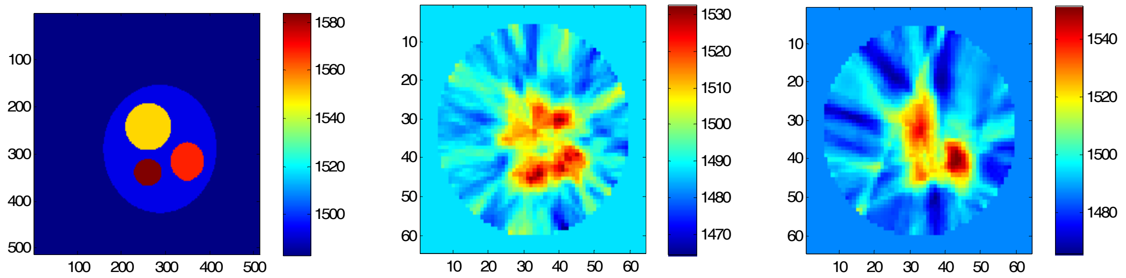
3.1 Simulated data

The sound-speed reconstruction was first tested on synthetic data. The simulation software was implemented to mimic the Karlsruhe 3D USCT system in the geometry and the data acquisition scheme. The radiofrequency signals were generated assuming propagation of spherical waves, with centre frequency of 3 MHz and bandwitdh of 1.2 MHz. Frequency-independent attenuation along the propagation path was implemented. The propagation path between each emitter and receiver was assumed straight, i.e. no refraction was simulated. The resulting synthetic radiofrequency signals were distorted by additive Gaussian white noise. The signal-to-noise was set to 11 dB, which corresponds to the ratio estimated from the data measured using the Karlsruhe 3D USCT system. The simulated object was a simple model of breast immersed in water (Fig. 1a). It consists of four homogeneous regions of cylindrical shape, with axes of the cylinders parallel to the axis of the USCT water tank cylinder. The sound-speed in the breast tissue and in the lesions was set to physiological values reported in [5] for normal breast tissue, cyst, carcinoma and fibroadenoma. The attenuation coefficient was constant for all tissues, set to 0.7 dB/cm (typical value for soft tissues).

The accuracy of the estimated sound-speed maps for various focusing apertures was evaluated in terms of the mean squared difference between the estimated map and the reference sound-speed map used for synthetic-data generation. The results for some focusing apertures are shown in Table 1. Example images are given in Fig. 1. The focusing scheme improves both the accuracy and spatial consistence of the sound-speed maps.

Focusing	no focusing	receiver focusing	emitter and receiver focusing	emitter and receiver focusing
Aperture size (emitter / receiver) [mm x mm]	- / -	- / 8x8	16x16 / 24x24	32x32 / 24x24
Mean square error [$(m/s)^2$]	208	195	185	167

Tab 1. Mean square errors of sound-speed maps for simulated USCT data.

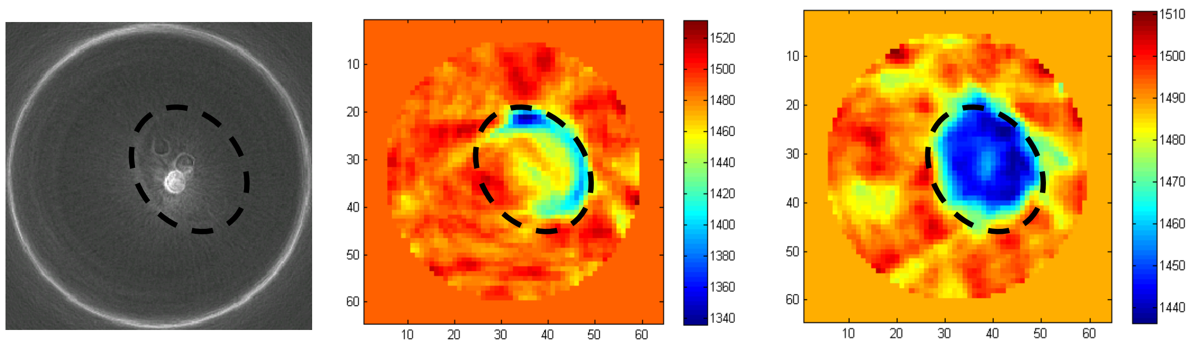


(a) (b) (c)

Fig 1.Sound-speed maps for synthetic data (coulour-encoded sound-speed values are given in m/s). (a) Reference sound-speed image. (b) Reconstructed sound-speed image with no focusing. (c) Reconstructed sound-speed image with focusing on the receiver and sender side (aperture size: emitter / receiver 32x32/24x24 mm]).

3.2 Measured phantom data

The sound-speed reconstruction with synthetic-aperture focusing described above was tested on data recorded with the Karlsruhe 3D USCT system on a breast phantom with embedded cyst-mimicking lesions (CIRS triple modality breast phantom). To evaluate visually the sound-speed maps based on known outlines of structures in the selected slice, a reflectivity image was reconstructed using an algorithm described in [3] (Fig. 2a). Sound-speed maps in the selected slice are shown for no focusing (Fig. 2b) and focusing on both the sender and receiver sides (Fig. 2c). The example images show that focusing substantially improves the spatial consistency as expected. The sound-speed of the main-body material was in accordance with the phantom specifications (approximately 1450 m/s). The focusing parameters were as follows: receiving aperture 7 x 7 virtual receiving-transducer positions (24 x 24 mm) in the horizontal and vertical direction, respectively; emitting aperture 3 x 3 virtual emitting-transducer positions (16 x 16 mm) in the horizontal and vertical direction, respectively.



(a) (b) (c)

Fig 2. Measured breast phantom image data; black ellipse indicates the breast outline according to the reflectivity image. (a) Reflectivity image. (b) Reconstructed sound-speed image with no focusing. (c) Reconstructed sound-speed image with focusing on the receiver and sender side. Coulour-encoded sound-speed values are given in m/s.

4 Discussion and Conclusions

The presented synthetic-aperture focusing improves the reconstruction of sound-speed images in case of sparse distribution of small transducers in USCT. The synthetic aperture size has to be chosen as a compromise. Larger aperture leads on one hand to better suppression of diffraction and higher SNR, while, on the other hand, decreasing the spatial resolution of the reconstructed images. Optimal focusing parameters are under research presently. The focusing algorithm will be also further extended to account for spatially varying sound-speed.

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