The USCT reference database

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Abstract

Ultrasound Computer Tomography (USCT) is an emerging technology mostly aimed at breast cancer imaging. Following the idea of open science a USCT reference database is established with open and easy to use data and code interfaces. The aim is to promote and facilitate the exchange of available reconstruction algorithms and raw data sets from different USCT devices throughout the growing USCT community. Additionally, the feedback about data and system architecture of the scientists working on reconstruction methods will be published online to help to drive further development of the various measurement setups.

Keywords: USCT, reference database, open science, open access, open source

1 Introduction

The Ultrasound Computer Tomography (USCT) reference database aims on applying available image reconstruction algorithms on provided USCT data in order to establish intercommunication and standards for an open data interface. The raw RF data sets and software for data access are available via the USCT database web page and the linked data and code repositories [1]. The long term goal of this work is to build a free and open licensed reference database which is available for the whole community. We expect this to enable reproducible comparison of image reconstruction algorithms and USCT systems. In addition, we aim to establish user friendly and easy to use interfaces, standards and data formats between the different USCT systems and their reconstruction algorithms, software and data formats.

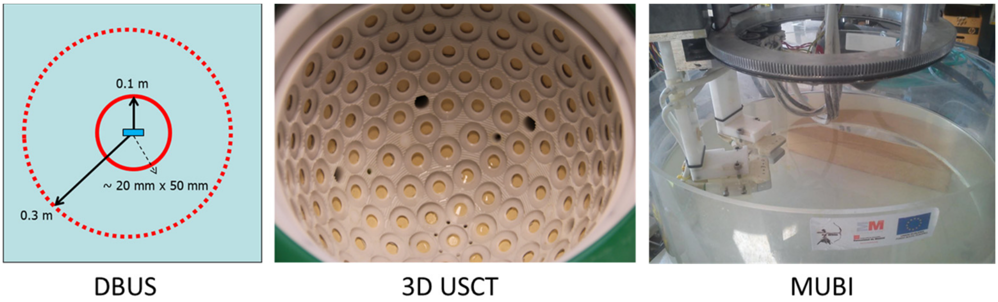

Figure 1: The three scanning systems of the USCT database; (left) Delft Breast Ultrasound Scanner (DBUS): 2D system, single transducers with 0.5 MHz center frequency, emitter radius 0.3 m and receiver radius 0.1 m; (center) 3D KIT USCT: 3D system, single transducers with 2.5 MHz center frequency, semi-elliptical aperture with 24 cm diameter and 17 cm height; (right) MUBI system: 2D system, two 3.5 MHz, 128 elements and 0.22 mm pitch arrays 95 mm radius, pulse-echo and through-transmission modes.

2 Reference database

Currently three systems with rather different transducer aperture and ultrasound frequency range provided raw data sets for the USCT database: Delft Breast Ultrasound Scanner (DBUS), KIT's 3D Ultrasound Computer Tomography system (3D USCT) [5] and Multimodal Ultrasound Breast Imaging System (MUBI) [6]. All data sets are provided with data access interface software. The source code is freely available and an issue tracker is provided at a Github repository. The materials of the USCT database are provided using a free and open license, i.e. the BSD 3-clause license for code and data, allowing free use and publication of results.

2.1 Delft Breast Ultrasound Scanner (DBUS)

The Delft Breast Ultrasound Scanner (DBUS) is depicted on the left-hand side of Figure 1. The system consists of a water tank with dimensions 0.75 m x 0.75 m x 0.65 m with a water level of 0.45 m. The temperature of the water is continuously monitored via thermocouples and kept constant within 1^{o}C using heating mats and a temperature controller. On top of the system, two rotary stages (LG Motion LGR1090-PD), controlled by motor drivers (Parker), are mounted. The first rotary stage rotates the object, the second the receiver (0.5 MHz, Panametrics V318). The source, which is identical to the receiver, is mounted at a fixed position in the corner of the tank.

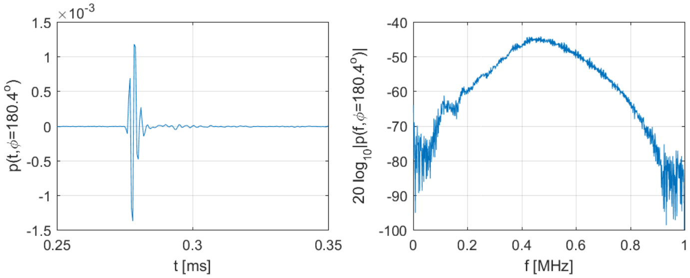

Figure 2: The RF data measured with the DBUS system in absence of an object; single A-scan in time (left) and frequency domain (right).

In this way a 2D tomographic scan of the object is obtained. For each A-scan, an electric pulse with a center frequency of approx. 0.5 MHz is generated by an arbitrary wave form generator (Agilent 33250A), amplified (Electronics and Innovation 210L 40 dB), and successively damped using a variable attenuator (JFW Industries, 50BR-036). The resulting wave field is measured using an identical transducer connected to a 14 bit A/D converter (Spectrum M3i.4142-exp - PCI) which is set to a sample rate of 400 MHz. For each A-scan, in addition to the raw (unfiltered) RF data, information such as temperature, source and receiver positions, etc. is stored. Together with a scan including an object, a scan in absence of an object, referred to as an empty scan, is made for reference. Figure 2 shows an example A-scan, presented in time and frequency domain, corresponding to a measurement with the source and receiver facing each other.

Two data sets are provided by the TU Delft. The first data set is made in absence of an object and can be used as reference measurement. It covers one source and 450 receiver positions equally distributed over 360°. The second data set is an agar based phantom with dimensions of 20 mm x 50 mm, and covers 45 source and 450 receiver positions, all equally distributed over 360°. The tissue mimicking phantom has a volume density of mass of approx. 1004 kg/m^3 and a speed of sound of approx. 1479 m/s. However, care has to be taken with these values as the conditions under which these values have been obtained may deviate from the actual scanning conditions. The three inclusions were generated by embedding drinking straws in the agar based phantom during curing. Prior to scanning the object, the straws were removed and the inclusions were filled with water.

2.2 KIT's 3D Ultrasound Computer Tomography system (3D USCT)

The KIT's 3D Ultrasound Computer Tomography system (3D USCT) is depicted in the center of Figure 1. The device has a semi-ellipsoidal 3D aperture. Approx. spherical wave fronts are generated by each emitter at 2.5 MHz and with a bandwidth of 1.5 MHz at -6 dB. The semi-elliptical aperture has a diameter of 26 cm and a height of 16 cm. Rotational and translational movements, so-called aperture positions, of the complete sensor system create additional virtual positions of the transducers.

The 2041 individual transducers are either operated as emitter (628) or receiver (1413). The transducers have opening angles of 38.2° (standard deviation ±1.5°) at -6 dB. Four emitters and nine receivers are grouped together including pre-amplifier and control electronics in so-called Transducer Array Systems (TAS). Each of the 157 TAS contains a temperature sensor for tracking the temperature distribution within the water basin and the shift at each TAS position during measurements. Additionally, two calibrated PT100 temperature sensors are embedded in the TAS holder to enable increased accuracy.

The data acquisition is carried out with an FPGA based system, which can store up to $80\ GByte$ of A-scans [4]. The digitalization is performed by 480 parallel channels ($12\ Bit$ at $20\ MHz$), enabling data acquisition at one aperture position in approx. ten seconds. After digitization, the parallel data streams are processed as follows: First, the data streams are bandpass filtered (1.67 to $3.33\ MHz$ at $-60\ dB$). Next, the data rate is reduced by a factor of six by performing bandpass undersampling. Finally, the reduced data is stored in the internal memory buffer. Using this approach up to 47 data sets at different aperture positions can be stored in one data acquisition step. A detailed description of the 3D USCT system can be found in [5].

The emitters are excited with a coded excitation signal, e.g. frequency coded chirps can be applied to increase the signal-to-noise ratio of the data. Also the gain of the receiving channels is set individually based on an initial measurement. The applied coded excitation, the individual gain, the temperature data and the spatial positions of the aperture are stored along with the A-scans for each measurement and can be used for signal (pre-) processing and image reconstruction.

Three data sets of different phantoms are provided, each with an empty scan acquired at the same day as the phantom and identical settings of the system's parameters. Figure 3 shows fotos of the phantoms and exemplary reconstructions.

Gelatin 3: The phantom consists of a gelatin phantom with diameter of approx. 0.07 m at the bottom and 0.10 m at the top, a height of approx. 0.13 m of which approx. 0.10 m where immersed into the USCT aperture. The speed of sound of the gelatin was approx. 1515 m/s. The gelatin was embedded in a plastic cup. Two inclusions were generated by embedding drinking straws with diameter 5 mm in the gelatin during curing. Prior to scanning the object, the straws were removed and the inclusions were filled with water. The phantom was positioned approx. centrally in the 3D USCT aperture.

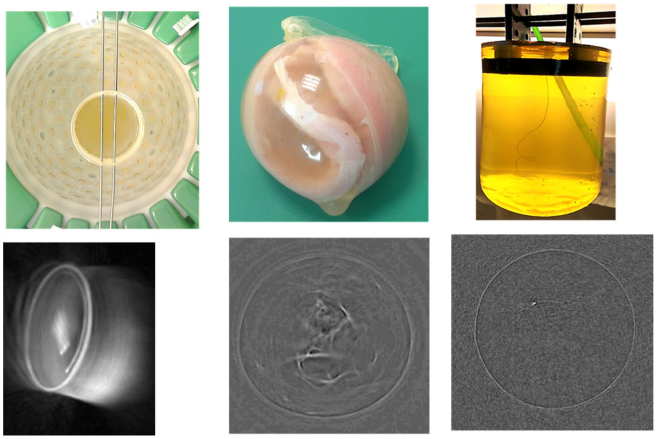

Figure 3: Phantoms scanned; (top) photo, (bottom) reconstruction using different reconstruction algorithms. From left to right: Gelatin 3 phantom reconstructed with SAFT in low resolution and displayed as maximum intensity projection to enhance the visibility of the bottom of the plastic cup, turkey phantom reconstructed with SAFT, and finally nylon thread phantom with speed of sound corrected SAFT reconstruction.

Turkey phantom: Two olives without stones where embedded into a turkey steak. This steak was then embedded in a condom and filled with gelatin. The resulting phantom has a diameter of approx. 9 cm. The phantom was positioned approx. centrally in the 3D USCT aperture. The turkey steak had an approximate sound speed of > 1550 m/s while the olives had a sound speed of approx. 1450 m/s.

Nylon threads: The phantom consists of a gelatin cylinder with both diameter and height of approx. 10 cm. In this cylinder a nylon thread of diameter 0.2 mm is embedded. The phantom was centrally positioned in the 3D USCT aperture.

2.3 Madrid's Multimodal Ultrasound Breast Imaging System (MUBI)

The Multimodal Ultrasound Breast Imaging System (MUBI) is a joint development of the Spanish National Research Council (CISC) and the Complutense University of Madrid (UCM), and it is intended to be a flexible platform for multi-modal ultrasound imaging research, mainly oriented to breast diagnosis [7].]. Up to know three imaging techniques were implemented: Phased-array, acoustic radiation force imaging [8] (both with full angle spatial compound), and ultrasound computed tomography [9].

The system is formed by two 3.5 MHz, 128 elements and 0.22 mm pitch arrays (P2-4/30EP, Prosonic, Korea) that rotate with 95 mm radius into a water tank, controlled by independent stepper motors with an angular resolution of 0.1º. A 128 channel full parallel ultrasound system (SITAU-112, Dasel, Spain) is used for excitation and signal acquisition.

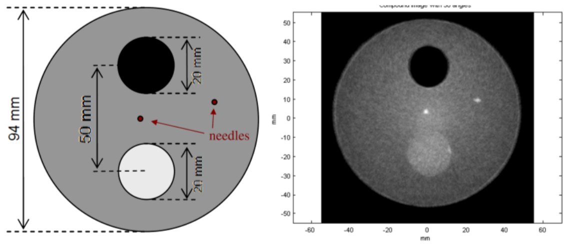

Figure 4: MUBI tissue mimicking phantom: technical drawing (left) and reconstructed with full angle spatial compounding (right).

While only one array can be used as emitter, both of them can act as receivers, allowing pulse-echo and through-transmission operation modes. The system is able to perform emission and reception beamforming in real-time implementing image compounding. It also gives access to the individual signals received by each array element for USCT reconstruction. The acquisition scheme for USCT follows the fan-beam approach of CT systems.

The 2D MUBI USCT data consists of two data sets. The provided phantom data set contains a circular scan of the tissue mimicking phantom, based on water, gelatin, graphite powder and alcohol. It includes a homogenous background with two cylindrical hollows: one filled with water and the other filled with a gelatin preparation with different proportions. Two 0.25 mm diameter steel needles were inserted in the approximate locations shown in Figure 4 left. Furthermore, a second dataset with the same acquisition parameters but without phantom (only water) is provided for calibration purposes. Figure 4 shows the phantom's technical drawing and a full angle spatial compounding reflectivity image.

3 Results of first release

As a result of the joint initiative, a database has been set up. In addition, a kick-off event for the USCT database took place at the USCT data challenge at SPIE Medical Imaging 2017 [3]. The aim of this event was to bring together experts from the USCT community to identify best practices, as well as to establish specifications for interfaces and to carry out a first comparison of reconstructed images. Six posters were presented and three detailed field reports of groups applying their image reconstruction to the provided data were submitted. The challenge hosted a two-hour panel discussion, where the panelists and the audience discussed the experiences on applying the currently available datasets and future directions.

As example the field report of the KIT team (main author Torsten Hopp) is summarized in the following paragraphs.

Both datasets of the 2D systems, i.e. the DBUS and the MUBI system, were tested with the KIT reconstruction software. For transmission tomography, a ray based algebraic reconstruction techniques (ART) [10] was used and for reflectivity imaging a 3D synthetic aperture focusing technique (SAFT) [11] including, if possible, sound speed correction.

For the DBUS dataset sound speed reconstructions performed with ART did not recover the rectangular shape of the imaged phantom. The imaged area appears nearly homogeneously with a sound speed of approx. 1491 - 1493 m/s.

The only contrast in the image seems to origin from the different water temperature at which the A-scans were acquired. Consequently the reflectivity reconstructions were performed with uncorrected SAFT using the average of the given water temperature to compute the sound speed. A-scans for reconstruction were selected by limiting the angle between emitter and receiver normal to 120°. Transmissions signals were removed in a preprocessing step. The pixel resolution was 0.2 mm leading to an image size of 996 x 996 pixels for the area reconstructed to cover the circle covered by the receiving transducer (Figure 5).

The computation time using a single NVidia GeForce GTX Titan GPU was approx. 8 s of which approx. 1 s was the computing time for the actual SAFT processing. A detail view of the phantom and its reconstruction is given in Figure 5.

For the MUBI system sound speed and attenuation images were reconstructed with an ART-based method using a CPU implementation.Figure 6 (top left) shows the result of the speed of sound reconstruction and attenuation reconstruction (top right). The phantom can be clearly distinguished from the water background. The water-filled hollow of the phantom can also be distinguished (lower sound speed area on the right).

Due to the limited resolution of the reconstruction method, the embedded needles are not visible. Subsequently we used the reconstructed sound speed maps to apply sound speed corrected SAFT. The results are given in Figure 6 bottom. The inner structures as well as the outline of the phantom are focused considerably better when applying the sound speed corrected SAFT algorithm. Both needles as well as the water-filled hollow are clearly visible, the second hollow with a different mixture of gelatine can be partly delineated in the lower part of the phantom.

The overall experience with the provided datasets was very positive. Using the interface software, the signal data and according metadata could be retrieved within minutes. For both datasets the KIT algorithm interfaces had to be adapted in order to apply reflectivity and transmission reconstruction, this adaption could be done in roughly one day per USCT system and modality. The images were mostly obtained with the basic parameter settings. Optimizing the parameters and methods to enhance the image quality would require additional time and insight into algorithms, systems and data.

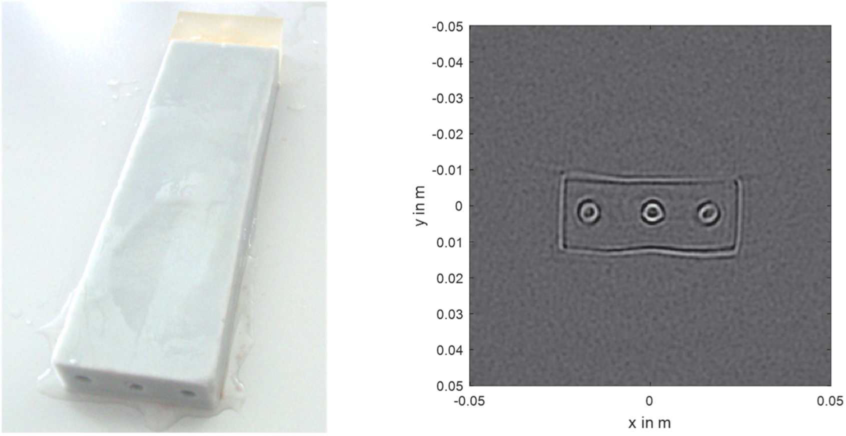

Figure 5: DBUS agar-based phantom: photo of the phantom (left) and reconstruction with 3D SAFT (right).

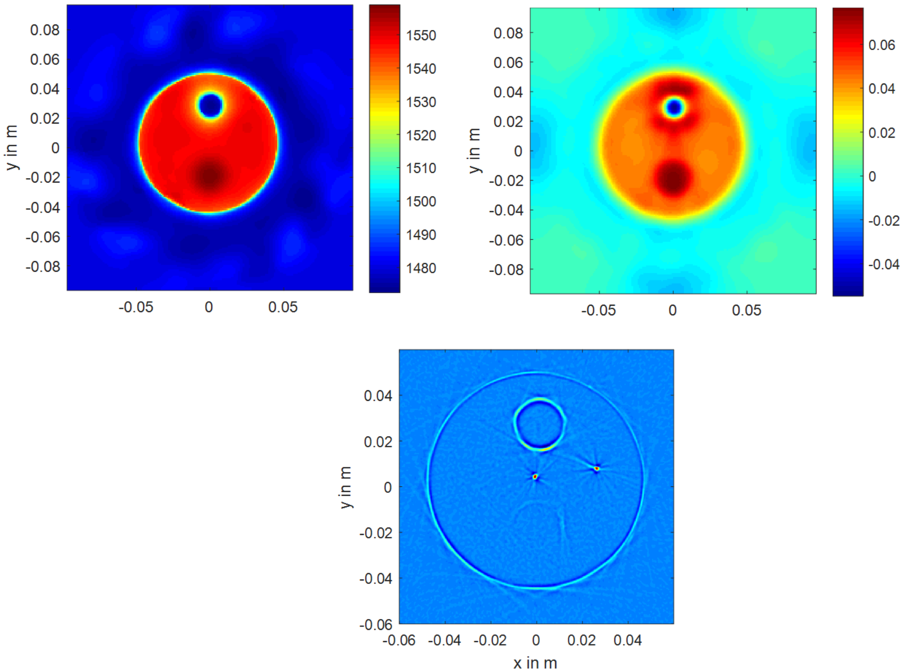

Figure 6: MUBI tissue mimicking phantom: speed of sound in m/s (top left) and attenuation reconstruction in dB/cm (top right); 3D SAFT corrected with reconstruced sound speed and attenuation map (bottom). Axes in m.

The reconstruced images are very promising. Sound speed and attenuation imaging was successfully applied to the MUBI data. Despite the ray approach, which comes with limited resolution, the reconstructed images were able to derive the phantom outline and both large inclusions. The rectangular shape of the DBUS phantom with the same algorithms could not be recovered. Further analysis is needed to identify the potential problems and/or limitations of the method or data. Additional metadata and knowledge about the system (e.g. excitation pulse, possible delays in the signal chain, temperature distribution in the water basin) could contribute to a deeper analysis.

For both systems, the phantoms could be reconstructed with the SAFT based reflectivity reconstruction. In case of the MUBI data, the data provided was not optimal for reflectivity imaging as there is only the ‘fan beam’ data provided. In consequence mostly the forward scattering is imaged, which limits the resolution and contrast of the reflectivity images.

Due to the GPU accelerated implementation of SAFT, sound speed corrected reflectivity images could be reconstructed in several seconds. Nevertheless there is still a large potential to speed up the reconstructions by optimizing data flows and parallelize data read-in and preprocessing.

4 Conclusion and future work

We expect the online database to enable reproducible comparison of image reconstruction algorithms and USCT systems. It should establish user friendly and easy to use interfaces, standards and data formats between the different USCT systems and their reconstruction algorithms, software and data formats. Further challenges are planned, e.g. comparing the image quality and/or computational performance obtained by different algorithms. Finally, other groups are invited to join in and participate.

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