Iterative Intraoperative Digital Tomosynthesis Image Reconstruction using a Prior as Initial Image

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ABSTRACT

The efficacy of interventional treatments highly relies on an accurate identification of the target lesions and the interventional tools in the guidance images. Whereas X-ray radiography poses low doses to the patient, its weakness is in the superposition of the different image structures in a 2D image. Cone-beam computed tomography (CBCT) might look ideal providing exact 3D information, however this is at the cost of a higher radiation dose, longer imaging time, and more space requirements in the operating room. Introducing some depth information with relatively low dose, and requiring less space, digital tomosynthesis (DTS) is a potential candidate for guiding interventions. However, due to the few number of projections and to the limited angle acquisition, DTS has poor depth resolution. Since high quality patient-specific prior CT scans are usually performed prior to the intervention for diagnosis or to plan the intervention, and given that such images share a fair amount of information with the intraoperative DTS images, we propose in this work a prior-based iterative reconstruction framework to improve the intraoperative DTS image quality. The framework is based on registering the prior CT image to an intermediate low-quality intraoperative DTS image, then iteratively re-reconstructing the intraoperative DTS image using the coregistered prior CT as the starting image. We acquired prior CT and intraoperative CBCT data of a liver phantom and simulated some intraoperative DTS projection images using a spherical ellipse scan geometry. Our results show a great improvement in the DTS image quality with the proposed method and prove the importance of choosing a good starting point for the iterative DTS reconstruction.

Keywords: Digital tomosynthesis, iterative reconstruction, prior information

1. INTRODUCTION

Imposing less space restrictions and less radiation dose than cone-beam computed tomography (CBCT) on the one hand, and introducing depth information to X-ray radiography on the other hand, digital tomosynthesis (DTS) could potentially make a leap in guiding interventions. During this procedure, the C-arm acquires a sequence of few projections over a limited angular range and provides a quasi 3D image. On top of the streaking and ringing artifacts due to the low number of projections, DTS images suffer from geometric distortions due to the limited angle acquisition. The resolution in the reconstructed volume is anisotropic, more precisely, DTS images have poor resolution in the depth direction. For this reason, DTS has not reached yet its application in real clinical interventions where having high quality guidance images is crucial in order to navigate the interventional tool (e.g. needle) to the target location or to confirm the tool-in-lesion. In this context, we recently proposed a new C-arm-based multi-directional spherical ellipse DTS scan trajectory to improve the depth resolution of the standard linear DTS.[1] In this work we investigate the further improvement of intraoperative DTS image quality by exploiting patient-specific prior information. Usually, prior to the surgical intervention, a high quality

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patient-specific CT scan is performed for diagnosis or for treatment planning. A key observation is that the prior CT image and the intraoperative one share a fair amount of anatomical information. The only deformations between the two images are caused by patient motion, and the positioning of the surgical instrument. Many iterative prior-based reconstruction approaches have been proposed for CT problems with insufficient data.[2,3] However, the priors have been always included in the body of the iteration whereas the initialization has been overlooked. As we are dealing with a highly under-determined problem with DTS reconstruction where the nullspace is huge and only a tiny part of the image information is measured, the choice of the starting image is potentially crucial. Therefore, we propose in this work a framework based on the registration of the prior CT image to an intermediate intraoperative DTS image followed by an iterative reconstruction of the intraoperative DTS image using the co-registered prior as a first guess.

2. MATERIALS AND METHODS

2.1 Data

The Quant CT-Training Phantom from Cascination* was used in this work. It includes a liver with some lesions, a spine, the ribs, and a portal vein. The prior CT volume was acquired at 70 KVp with a Siemens SOMATOM X.cite scanner (Siemens Healthcare GmbH, Erlangen, Germany). The acquired image dimensions were $768 \times 768 \times 266$ voxels with a voxel size of $0.479mm \times 0.479mm \times 1mm$. The intraoperative CBCT volume was acquired using a Siemens ARTIS Icono C-arm scanner (Siemens Healthcare GmbH, Erlangen, Germany) at 87.5 KVp. The CBCT image dimensions were $512 \times 512 \times 368$ voxels with a voxel size of $0.49mm \times 0.49mm \times 0.49mm$. To mimic an interventional scenario, an ablation needle was inserted in the phantom before acquiring the intraoperative CBCT volume.

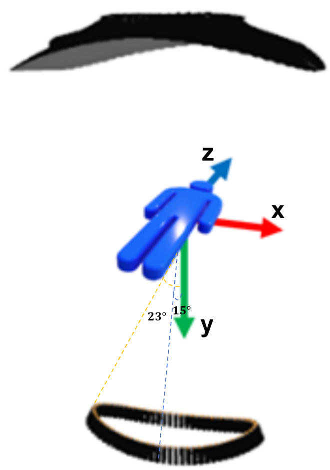

Figure 1. Illustration of the spherical ellipse DTS scan trajectory.

To simulate the intraoperative DTS projection images, the CBCT volume was forward-projected according to a newly proposed spherical ellipse scan geometry.[1] This protocol assumes that the source and the detector are mounted on a robotic C-arm and each moves along a spherical ellipse orbit. Fig. 1 illustrates the spherical ellipse acquisition setup. Mounted in opposite to the X-ray source, the detector performs an in-plane rotation in a way its rows are kept tangent to the scan trajectory. The detector is composed of 616×480 pixels with a 0.616 mm pixel pitch. The source to iso-center distance is set to 785 mm and the source to detector distance is set to 1200 mm. This trajectory is defined by two tomographic angles. In this work, we fixed the angles to $\pm 15°$ and $\pm 23°$ and simulated 72 projection views. The system acquisition has been implemented in the open-source Computed Tomography Library CTL†.[4]

*https://www.cascination.com/en/quant-training-phantom

†code available at:
https://gitlab.com/tpfeiffe/ctl/-/tree/master/examples/TomosynthesisEllipticalTrajectory

2.2 Registration and Reconstruction

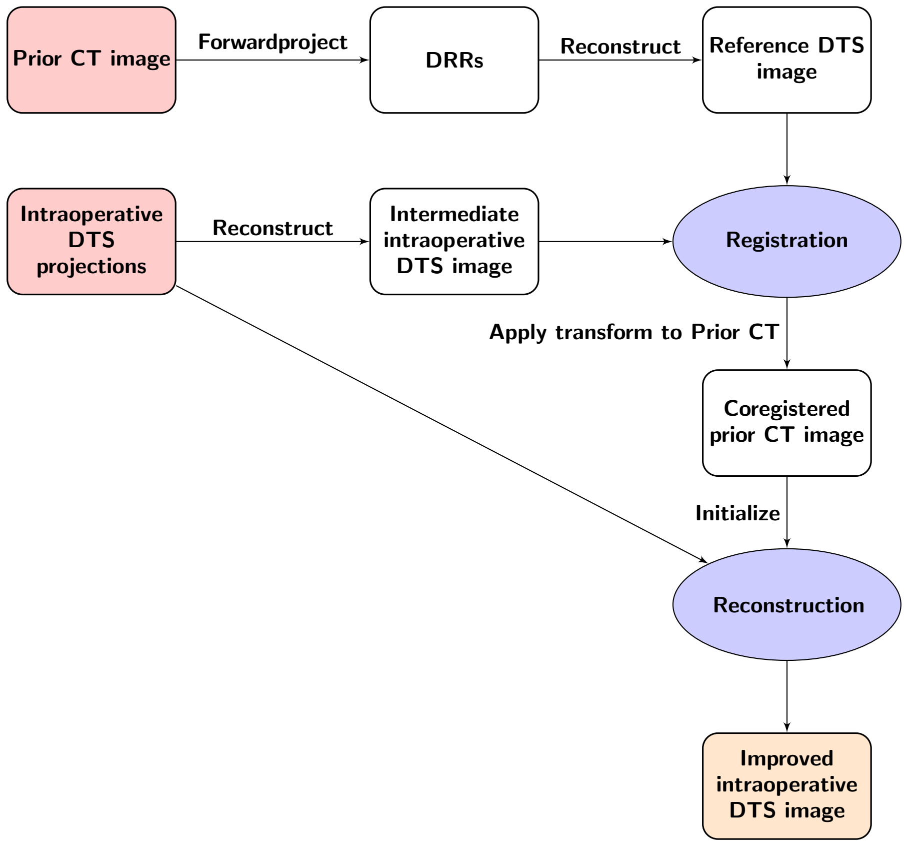

Figure 2. Flowchart of the proposed reconstruction method.

The proposed framework is illustrated in Fig. 2. To register the prior CT volume to the current intraoperative anatomy, an intermediate intraoperative DTS image is reconstructed from the intraoperative DTS projections. An iterative algebraic reconstruction technique (ART) with an ordered-subsets scheme[5] is used. The relaxation parameter is estimated as in Ref. 6. At this stage the initial image voxels are set to zero. It was shown in Ref. 7 that the complexity of DTS resolution characteristics limits the accuracy of DTS-CT registration and a DTS-DTS registration is more precise. Therefore, from the prior CT volume we generated a set of reference digitally reconstructed radiographs (DRRs) using the same intraoperative DTS scan geometry described above and we reconstructed a reference DTS image. At this step the prior CT image was downsampled to $512 \times 512 \times 177$ voxels with a voxel size of $0.7187mm \times 0.7187mm \times 1.5mm$. Here it worth be noted that the reconstruction of the reference DTS image can be performed before the intervention as soon as the prior CT image is available. We performed the registration of the reference DTS image to the intraoperative DTS image using a rigid registration employing the Mattes mutual information as a similarity measure. We used the registration toolbox ANTsPy.[8] The registration transform was then applied to the prior CT image. The intraoperative DTS projections are iteratively re-reconstructed using the co-registered prior CT as a first guess and including only a positivity constraint.

2.3 Results

The registration results are shown in Fig. 3. One axial slice and one coronal slice where the needle tip and a liver lesion exist are shown in the upper row and the lower row respectively. Fig. 3(a) and 3(b) illustrate the prior CT volume and the intermediate intraoperative DTS volume (zero-initialized ART) respectively. The co-registered prior CT volume is shown in Fig. 3(c). For reference the same slice of the intraoperative CBCT volume is shown in Fig. 3(d). Despite that we cannot examine the difference image due to the difference in

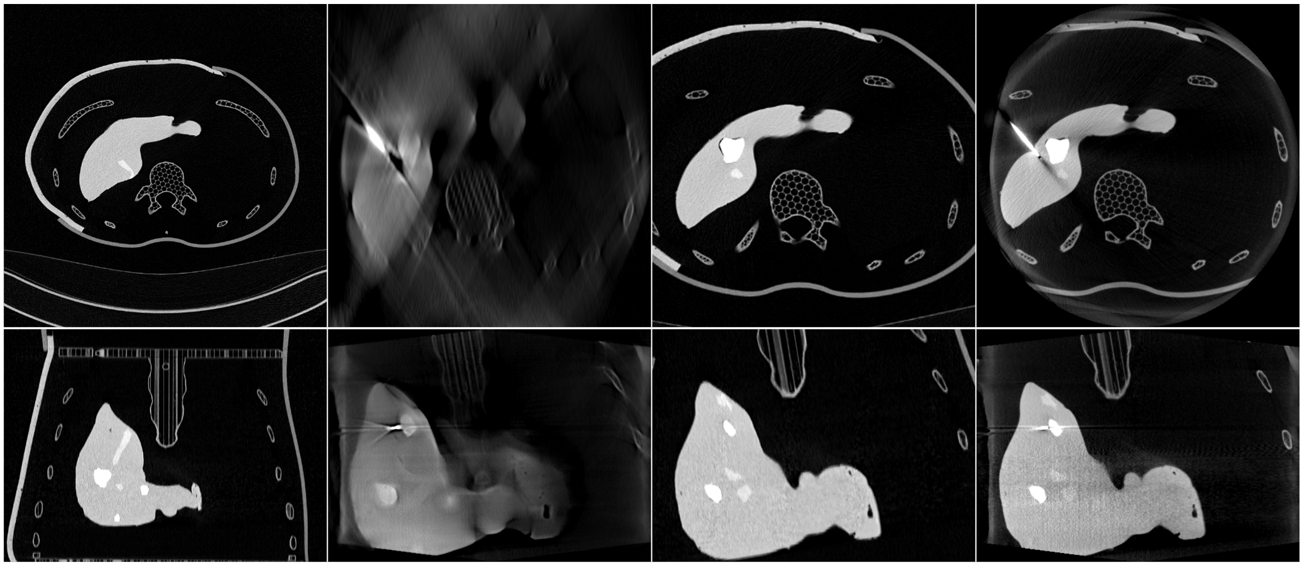

Figure 3. Registration results. (a) Prior CT, (b) intermediate intraoperative tomosynthesis, (c) coregistered prior CT, and (d) intraoperative CBCT. Upper row: one axial slice. Lower row: one coronal slice. Same slices are shown in (b), (c), and (d). The display window range is [-1000HU, 700HU].

intensity values between the CT and the CBCT images, it is evident from the visual inspection that the prior CT volume is well registered to the intraoperative volume. The liver, the spine, and the lesions seem accurately aligned in (c) and (d).

Fig. 4 illustrates the reconstruction results. For comparison the same axial slice is shown in the upper row and the same coronal slice is shown in the lower row. Fig. 4(a) shows the DTS reconstruction with zero-initialized ART, without including the prior. Fig. 4(b) illustrates the reconstructed image with our proposed method using the co-registered prior CT as a starting image. For reference the intraoperative CBCT image is shown in Fig. 4(c). As expected, without including the prior, DTS exhibits poor resolution in the depth direction, the lesion is blurred and barely visible and the spine as well. A considerable improvement in image quality is observed with the prior-initialized reconstruction. It looks much similar to the intraoperative CBCT. These observations are further validated in the line profiles plotted in Fig. 5 corresponding to the vertical (graph on the left) and the horizontal (graph on the right) lines highlighted in yellow in Fig. 4(c).

2.4 Discussion and Conclusion

In this work we proposed a prior-based iterative reconstruction framework to improve intraoperative digital tomosynthesis (DTS) reconstruction. We considered a high-quality prior CT volume is available prior to the intervention. We simulated intraoperative DTS projection images using a spherical ellipse DTS geometry.[1] The proposed framework is composed of two steps. First, the registration of the prior CT to the current anatomy, at this stage a reference prior DTS image simulated from the prior CT and an intermediate low-quality reconstructed intraoperative DTS image are co-registered, the registration transform is then applied to the prior CT. Second, an iterative ART reconstruction using the co-registered prior CT as a first guess is performed to further improve the intraoperative DTS image quality. The reference prior DTS can be reconstructed beforehand prior to the intervention as soon as the prior CT is available. While prior information have been incorporated in the iterative process itself in previous works, the initialization was mostly overlooked. In this work, we showed how important is the starting point of the iterative reconstruction in such a highly under-determined problem. A considerable improvement in the different structures visibility has been achieved. A still open question is how sensible is the reconstruction to insufficiently accurate registration. By the design of the method, information measured from

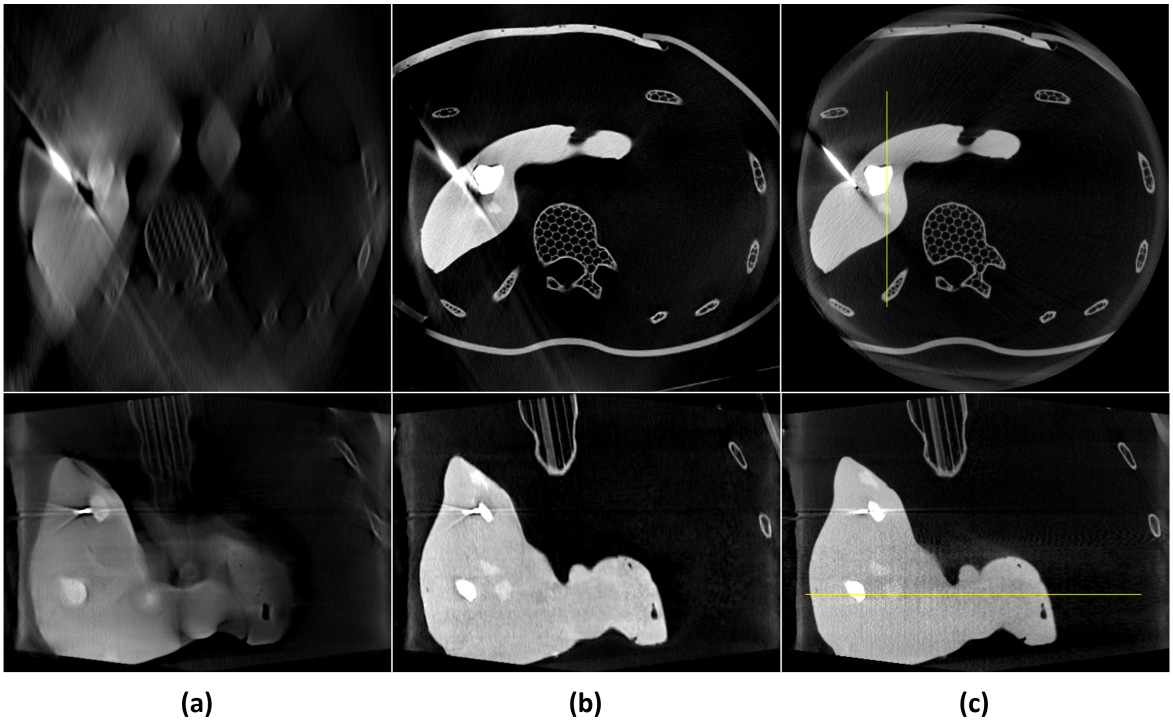

Figure 4. Reconstruction results. (a) zero-initialized ART, (b) proposed method (prior-initialized ART), and (c) intraoperative CBCT. Upper row: one axial slice. Lower row: one coronal slice. Same slices are shown in (a), (b), and (c). The display window range is [-1000HU, 700HU].

the tomosynthesis trajectory are included in the prior-initialized ART and all missing information are inherited from the co-registered prior. In case of inaccuracies in the registration, this may lead to wrong conclusions while interpreting the images. Therefore, clinical experts will be included in the evaluation process in the future. In the current work, we only considered a rigid motion between the prior and intraoperative states, this is probably valid for head interventions, however in many other interventions, such as in the lungs, the abdomen, and the liver, theses organs are prone to elastic motions. Considering such complex motions is the subject of current works. Moreover, how low can we go with the angular range and the number of projections will be further investigated.

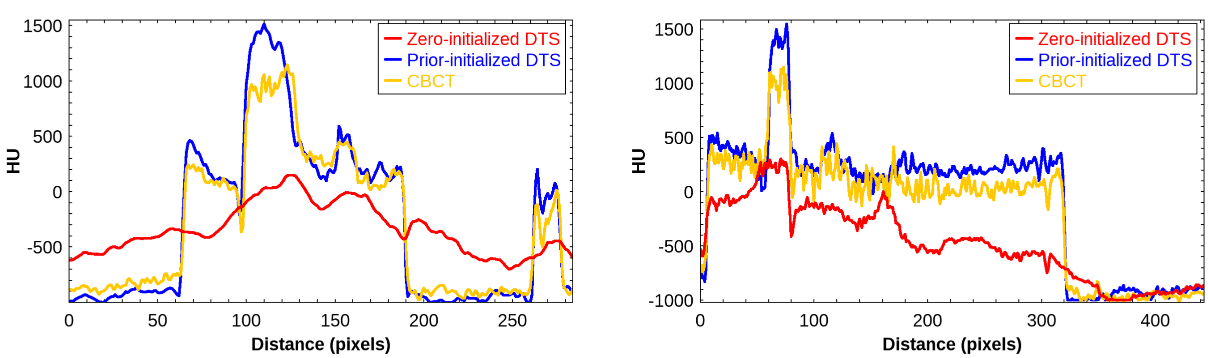

Figure 5. Profile plots of the two lines highlighted in yellow in Fig. 4 (left: in the axial slice and right: in the coronal slice).

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