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Enhancement of Region of Interest CT Reconstructions through Multimodal Data

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Abstract: Computed tomography (CT) scans are frequently used intraoperatively, for example to control the positioning of implants during intervention. Often, to provide the required information, a full field of view is unnecessary. Instead, the region-of-interest (ROI) imaging can be performed, allowing for substantial reduction in the applied X-ray dose. However, ROI imaging leads to data inconsistencies, caused by the truncation of the projections. This lack of information severely impairs the quality of the reconstructed images. This study presents a proof-of-concept for a new approach that combines the incomplete CT data with ultrasound data and time of flight measurements in order to restore some of the lacking information. The routine is evaluated in a simulation study using the original Shepp-Logan phantom in ROI cases with different degrees of truncation. Image quality is assessed by means of normalized root mean square error. The proposed method significantly reduces truncation artifacts in the reconstructions and achieves considerable radiation exposure reductions.

Keywords: ROI imaging, computed tomography, truncated projections, X-ray exposure reduction, multimodal imaging.

1 Introduction

Computed tomography (CT) enables the exploration of the internal anatomy without invasive surgical intervention. The routine allows to differentiate between different types of tissue based on the attenuation of X-rays. In terms of the tomographic principle, a slice image of the patient’s anatomy can be calculated from a set of projections recorded around the patient. Due to its high acquisition speed and the sensitivity to precisely distinguish individual materials within the body, CT enables intra-operative imaging that can be used to control the positioning of implants for instance. However, the major disadvantage of CT screening is the exposure to X-radiation, leading to statistical, as well as deterministic damages, caused by interactions between radiation and tissue [3]. These effects are not to be underestimated, which is why it is of high importance to limit the radiation exposure as far as possible in order to reduce the harmful influences of a CT scan. A possible strategy to reduce the X-ray dose for the patient is to restrict the area that is irradiated in each projection. This method is called region-of-interest (ROI) imaging and it can be applied whenever anatomical information is only required from a certain region within the patient. Unfortunately, ROI imaging substantially increases the difficulty of reconstructing the slice images due to missing information from the unexposed body parts. In this paper, a method is presented on how to estimate this missing information based on multimodal data. The resulting approximations are then used to significantly increase the image quality of a region of interest (ROI) reconstruction.

2 State of the Art

Region of Interest Reconstruction

Artifacts that occur in CT reconstructions from truncated projections are well-known to be problematic. Development of algorithms that aim to address this issue has been an important topic that is particularly prominent in C-arm CT technology. In 1979, Wolfgang Wagner developed one of the firsts approaches. He completed ROI CT scans by means of estimated intensity data on the one hand, and using the estimation of the body outline, on the other hand [1]. This method provided significant improvements on the image quality and contributed to the removal of structural artifacts. Another method, presented by Chityala et al., tried to adjust the dose exposure to a minimum outside the ROI, instead of preventing it completely, which led to a considerable reduction in reconstruction error [2]. Furthermore, investigations based on Grangeat’s fundamental relation were made. Evaluations indicated that an extrapolation through a simple ellipsoid, optimized with respect to these consistency conditions, has the ability to distinctly improve the naive reconstruction [4]. An optimized reconstruction algorithm, called "Approximate Truncation Robust Algorithm Computed Tomography" (ATRACT), was derived from the Feldkamp-Algorithm and improved by means of better filtering, allowing for high quality reconstructions with less sensitivity towards lateral truncation for C-Arm CT systems [5]. Within all these studies, the reconstruction of incomplete CT projections is commonly performed without using any kind of previous knowledge. However, a priori knowledge can im-
prove simple reconstructions, as shown by further studies. For example, previous CT data can be utilized to reconstruct an ROI dataset completely, even in sections outside the ROI[6]. Evaluation of the method revealed that this inversion is not stable enough. In summary, it is to be expected that a priori knowledge can lead to further enhancements of ROI reconstructions.

Registration of Multimodal Data
Multimodal data is usually acquired by means of several individual devices (e.g. ultrasound (US) or time-of-flight (ToF) cameras). While this allows the gathering of distinct information that might be beneficial for image reconstruction, it also introduces a variety of differing coordinate systems. Consequently, image registration needs to be performed in order to fuse this data. Since medical images represent information that are relevant for diagnostics, registration strategies must be selected with care to avoid undesired data alteration. The majority of approaches are based on gradient information in the data. The resilient backpropagation algorithm (iRprop) that basically evaluates local gradient information, as well as the covariance matrix adaption evolution strategy (CMA), based on Gaussian mutation, count to the newer approaches. More established methods are the Broyden-Fletcher-Goldfarb-Shannon Algorithm (BFGS), representing a quasi Newton process, and the Conjugate Gradient Descent Algorithm (CG) that detects local gradient minima or maxima, respectively [7]. Evaluations showed that the newer methods exceed the traditional ones, where the CMA method was more precise and the iRprop algorithm achieved faster computation times.

When it comes to CT–US registration, several studies evaluated the best way to implement such algorithms. It has been shown that the characteristics of bone-tissue-transmissions, caused through total reflection [8], can be used as an optimization parameter [9]. Alternatively, one can bypass the use of complex functional dependencies by simply mapping US data to CT using a linear model, as described in [10]. A conceptually different approach is based on markers that serve as a reference to solve the problem of registration. Marker-based methods lead to stable and good results, which already found their way to the market.

All presented studies show that registration of US and CT is a well investigated subject, thus, a broad portfolio of approaches is available.

3 Method

With the multimodal approach as presented, information is incorporated into the reconstruction of ROI CT data. In order to reduce artifacts that originate from the missing information in the truncated projections. Reconstruction is performed by means of conventional filtered backprojection (FBP). As a pre-processing step, incomplete CT projections are completed by an extrapolation based on time of flight (ToF) measurements of the objects surface as well as US images. The aim is, to use the information about tissue transitions, which show up in an US examination due to the different tissue echogenicities. Based on these transitions, the object is structured into compartments. These compartments are identified with certain material (e.g. tissue, bone or air). Using a priori knowledge about the typical absorption coefficients of these materials, the truncated CT-Data can be completed using a simulated CT forward projection. The entire processing chain is realized with Matlab (The MathWorks, Inc., Natick, Massachusetts, United States).

The first step is the processing of the surface information from the ToF camera. The shape of the object is extracted from the surface information and filled with an initial estimate for the absorption coefficient. This is selected by the user, such that it fits to most of the tissue in the determined slice. Afterwards a forward projection is applied, providing an initial data estimation for the section outside the ROI. This already reduces artifacts significantly, compared to the naive reconstruction. To further improve on the estimate, transitions between the measured CT data and the complementary estimation in the sinogram are leveled. This is done by computation of individual scaling factors for each projection. Furthermore, an averaging of the scaling factors is done afterwards, to smooth the lateral transitions between the projections.

In the second step, the US image needs to be registered to the initial reconstruction from the FBP of the projections that have been extrapolated using ToF data. Since US and CT depict different information, image gradients are used to find a transformation that allows to fuse both images. The regular step gradient descent proceeding is employed with a mean squares error metric to optimize the registration.

As a final step, the initial extrapolation is refined using the US information. Therefore, a segmentation of the registered US data is calculated through the watershed transformation. Subsequently, the user needs to assign the type of tissue to each detected compartment. Based on a pre-defined lookup table that contains a priori information for each of the materials (e.g. water, soft tissue, and bone), appropriate absorption coefficients are given to all segments. A forward projection is used once again to simulate CT projections of the refined extrapolation and thereby, compute the sinogram. Afterwards the same procedure as described in step one is used to adjust the data, by smoothing the transitions. The achieved results show improvements on the previous ones by adding further information through the use of US image information in the reconstruction.
4 Results

Simulation setup
This study is based on simulated data from the original Shepp-Logan Phantom (SL) and a thorax phantom. The simulations of US and ToF acquisitions are derived from the respective phantoms. All simulations guaranteed that identical anatomical slices are imaged, which is a simplification that can be reached through a procedure described in the literature [11]. Contour plots are used to provide a simple simulation of ToF data. To simulate the US modality, characteristic noise—described as a whisker-like appearance in [12]—in combination with a contrast degradation was applied. Moreover, both artificial translation and rotation have been performed to simulate different acquisition coordinate systems.

Evaluation criteria
For evaluation, 13 sets of projections with varying degree of truncation (centered around the middle point of the sinogram) are simulated and reconstructed with different amounts of a priori information. Here, the percentage of truncation refers the proportion of data that is cropped with respect to the maximum span of data across all projections in an untruncated sinogram. The quality of the resulting reconstructions is assessed by means of the normalized root mean square error (NRMSE) between reconstruction $X$ and the original phantom $Y$:

$$\text{NRMSE} = \sqrt{\frac{1}{N} \cdot \| X - Y \|^2}.\quad (1)$$

Since reduction of the radiation exposure is the main motivation in ROI imaging, a quantitative measure is used to describe the level of dose reduction. Therefore, a rough estimation that is calculated as the ratio of all the x-rays, used for the ROI to the entirety of x-rays in a complete dataset. As expected, the radiation dose reduction drops approximately linearly to a minimum of 11% for a truncation degree of 90%, which is a significant distinction compared to conventional CT imaging procedures.

Evaluation – Reconstruction error
To demonstrate the benefit of the introduced method, Figure 1 shows a reconstruction of the SL phantom from a projection set with 90% truncation compared to a naive FBP reconstruction without any projection extrapolation. For comparison a full field of view reconstruction (i.e. 0% truncation) is also provided. In addition to the reconstructions, contrast profiles along the central horizontal line are plotted in the bottom part of Figure 1. Whereas the naive reconstruction fails to provide any useful information, the reconstruction based on the US-extrapolation almost completely recovers the full field of view result. Due to small errors in the registration and the US characteristics, a structural error occurs, which can be observed as an incomplete bone segment. Furthermore, within the soft tissue area, there are intensity deviations, originating from the estimation of the CT values, since the estimated values do not exactly correspond to the real values. However, a strong similarity of the reconstructed contrast profile compared to the full scan can be appreciated. This is of particular interest, given that this setting features a dose reduction of almost 90%.

As shown in Figure 2, the benefit from US extrapolation is consistent for different truncation cases and leads to significant reductions in NRMSE compared to the naive reconstruction. The performance of the method essentially depends on the quality of the available a priori information. This is evaluated more closely using three different sets of prior knowledge (cf. Figure 2 (b)). Missing information on bone structures (green crosses) leads to a significant increase of the RMSE. The effect of withholding soft tissue information (blue crosses) seems to be similar, but with respect to its considerable contribution to the extrapolation area, the impact is less substantial compared to lack of a priori knowledge about bone structures.
Evaluation – Registration

The requirement for an appropriate extrapolation of truncated CT data—which is essential for an artifact reduced reconstruction—is a robust and precise registration procedure to fuse US and CT data. The implemented method worked well for the SL phantom as indicated through previous considerations. Increasing the degree of truncation leads to slightly worse registration results and can be described as an approximately linear correlation. Some uncertainties, however, occur when registering the US to CT data for the thorax phantom. The erroneous registrations lead to further artifacts. Still, results have substantially lower errors than those of a naive reconstruction, but full potential of the available prior knowledge might not be used. An attempt was made to increase the robustness of the registration, by preventing the influence of reconstruction artifacts during the registration. Although that results in slightly better registrations, those are still not reliable enough to realize a satisfying solution. Therefore, registration needs to be performed by means of superior algorithms, for example as described in Section 2. However, this was not considered here for means of simplicity.

5 Conclusion

As shown in the previous section, the extrapolation of truncated CT projections through ToF measurements and US data leads to significant improvements in terms of artifact reduction. This goes along with a considerable potential in radiation exposure reduction. As discussed, a weakness of the presented method lays in the registration process, used for the fusion of US and initial extrapolated CT data. This routine needs optimization in terms of stability and reliability. Alternatively, a referenced US system could be employed, working in the same spatial coordinate system as the CT system, which would remove the necessity of image registration. Since this study is intended to provide a proof-of-concept, a common filtered back-projection was used to reconstruct the images. Further adaptations, like advanced filtering (e.g. more global filter), could be deployed to suppress amplification of the artifacts. Moreover, a study on the applicability is indicated, since the manual submission of the \textit{a priori} information could potentially make it hard to integrate such a routine in the clinical workflow. Hereunto, a linear mapping from US to CT data, as mentioned in Section 2, could be applied to render the manual interaction unnecessary. As a next step, the algorithm will be adapted for real datasets, evaluating if the same significant improvements to ROI reconstructions are achievable for real data.

Author Statement

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