High-Density Object Removal from Projection Images using Low-Frequency-Based Object Masking

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Abstract. High-density objects, like catheters, pacemakers or even contrast agent-filled vessels, cause characteristic streak artifacts in computed tomography (CT). Similar to metal artifacts, these streaks can be reduced by removing the dense object using segmentation and interpolation. First, we compare state-of-the-art interpolation methods like linear, spline and higher-order methods to the Healing Brush technique. Second, a new method is presented, that extracts a low-frequency model of the dense object and restores the decomposed X-ray intensity of the remaining tissue. This method is henceforth called Subtract-and-Shift. Compared to standard interpolation methods, it retains the measured structure that is superimposed and dominated by the dense object. The extracted structure is then used to replace the segmented pixel intensities of the object. The introduced method is compared to state-of-the-art interpolation methods using in-vivo data. First preliminary results show that Subtract-and-Shift can be superior to these interpolation methods.

1 Introduction

Metal artifact reduction has been an active field of research since the beginnings of CT, especially in an interventional environment using C-arm CT. 3-D images are reconstructed from the projection images using filtered back-projection methods. These methods are sensitive to strong edges, like dense objects in a projection, due to a high-pass filtering of the measured projection data. Many of the clinical applications in C-arm CT have to deal with motion of organs like the heart or the lung. Dense moving objects, like a catheter in a heart, result in highly inconsistent data. A common solution to reduce resulting streak artifacts is to detect and replace this data with interpolated data. However, this is a challenging task, since important anatomical structure is often overlaid by the dense object and thus the underlying anatomy has to be guessed during interpolation to reduce artificial errors. Although many data interpolation methods exist, metal artifact reduction is usually done by linear interpolation [1]. Since, to the best of our knowledge, no quantitative comparison of interpolation methods for object removal from projection images exists, we are currently evaluating common interpolation methods as described in the next section. However, the dense object does not always absorb the energy totally. A meaningful measurement can still be provided. In such a case, the anatomy of tissue is overlaid by the dense object. A catheter, for example, can be assumed to have a tubular structure. The idea of our new approach is to extract the underlying tissue measurement from the object intensity in the projection image. The shape of the dense object is modeled as a low-frequent bias value and subtracted from the measured intensity value. The remaining tissue intensity can provide meaningful structure for an improved data interpolation. This method is called Subtract-and-Shift and makes use of this remaining structure. We present first results of an in-vitro evaluation of standard interpolation methods in Section 3 and show that linear interpolation outperforms the other methods. Then we present first in-vivo results of Subtract-and-Shift and compare it to the three best performing standard interpolation methods, showing that structure is indeed retained by our method, whereas it is lost by using the other methods.

2 Materials and Methods

Line-wise linear interpolation, line-wise polynomial interpolation (degree 4), line-wise cubic b-spline interpolation (70 control points), defect pixel interpolation in frequency space [2] (2000 iterations) and the "Healing Brush" algorithm [3] have been evaluated and compared to each other using in-vitro data.

For the evaluation of interpolation results, we used the root-mean-square-deviation (RMSD) and the standard deviation of the difference image (SDDI). To do this, a catheter phantom was digitally inserted into a projection image and the interpolated image compared to the original, catheter-free image. Both low- and high-contrast phantoms were used to evaluate the interpolation performance.

Our new algorithm works as follows: (1) Blur a copy of the input image using a Gaussian window and subtract it from the input image at the pixels identified as belonging to the object to be removed. (2) For each image line, calculate the offset between all pixels left of the object and the object pixels, and the offset between all pixels right of the object and the object pixels. Then shift the intensity values of pixels belonging to the object, linearly interpolating between the two offsets.

We argue that the object to be removed introduces a low-frequency, model-based intensity bias. Although it follows from the attenuation law that a linear shift in *logarithmic* image space is introduced by an additional object in the X-ray beam, we hypothesize this can be treated as a linear shift in image space as an approximation. By subtracting the low-pass filtered version of the object area from the input, the low-frequency bias is removed, only retaining high-frequency content, i.e. structure that was still visible through the object, albeit centered around intensity value 0. The latter is corrected for by shifting the high-frequency content to the level of surrounding pixels' intensities. Since important structure (e.g. bone, vessels, etc.) might pass through the affected area, this shift is adapted to both the left and right neighborhood by linearly interpolating between both offsets. As the preferred direction of filtering during

Table 1. Results of phantom interpolation (lc = low-contrast, hc = high-contrast).

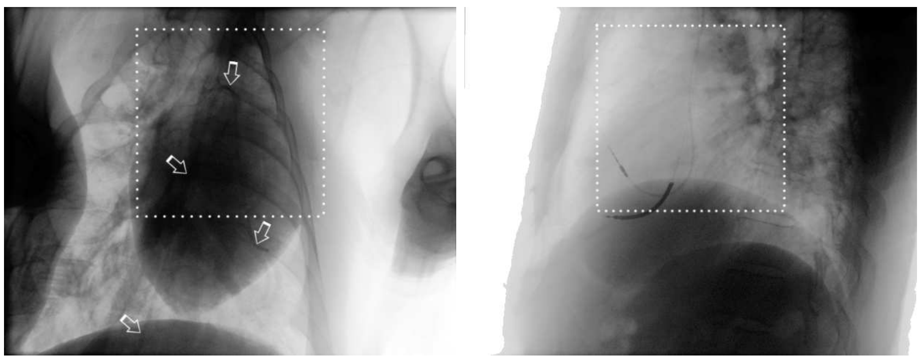
Interpolation Method	RMSD (lc)	RMSD (hc)	SDDI (lc)	SDDI (hc)
(Catheter image)	16.5821	35.0539	16.5809	35.0387
Linear	13.0513	15.8172	13.0504	15.8148
Polynomial	37.8894	37.0169	37.8649	36.9951
Spline	15.4711	17.5983	15.4688	17.5943
Defect Pixel	17.2252	17.9420	17.2216	17.9374
Healing Brush	29.9780	30.6537	29.9699	30.6433

back-projection is horizontal, we use a line-wise approach to this offset correction. Figure 1 shows two in-vivo images used to evaluate this algorithm and compare it to common interpolation methods.

3 Results

Table 1 shows the interpolation results of the phantom images. The first line shows the values for RMSD and SDDI of catheter image vs. catheter-free (original) image to give an upper bound on these values.

Figures 2 and 3 show the results of applying Subtract-and-Shift to the two example pictures, while Fig. 4(a) shows an intensity plot of the marked area (Fig. 2(a)), visualizing the two steps of the algorithm. Finally, Figure 4(b) shows an intensity plot of the right part of the catheter (same image line as in Fig. 4(a)), including the result of our algorithm, as well as the result of linear, spline and defect pixel interpolation.

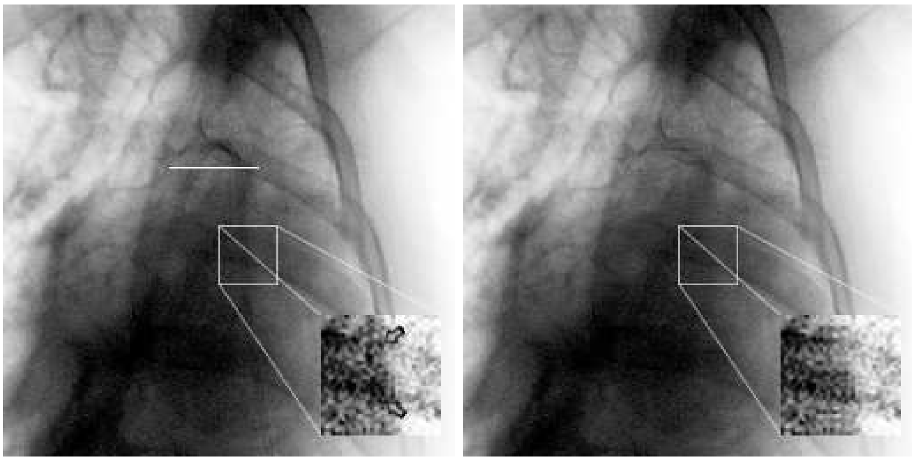


(a) Catheter (b) Pacemaker

Fig. 1. In-vivo images used to evaluate Subtract-and-Shift. The dotted frame is the area shown in the images in the next section. In image (a), arrows point towards the catheter.

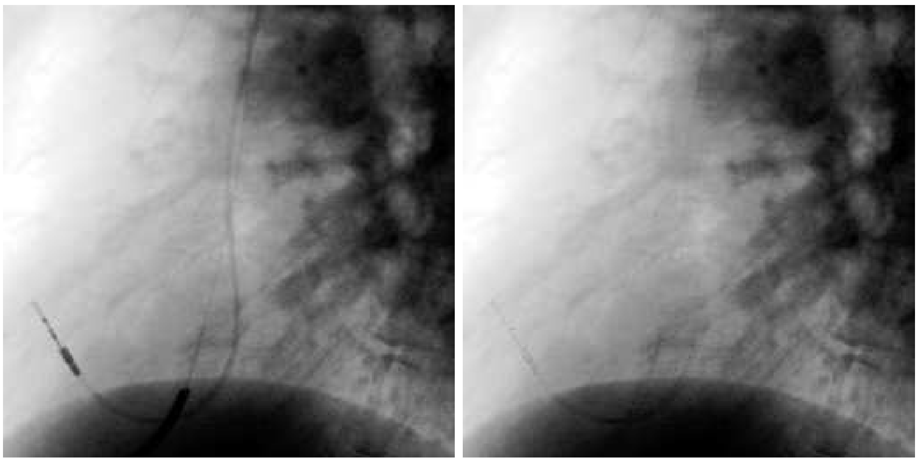
4 Discussion

From the absolute values of the results in Tab. 1, it can be seen that the interpolation results do not seem to be influenced much by the contrast of the phantom. It can also be seen that linear, spline and defect pixel interpolation perform best (in that order). While certainly producing visually pleasing results in photo manipulation, the Healing Brush introduced bigger differences to the original



(a) Original (b) Interpolated

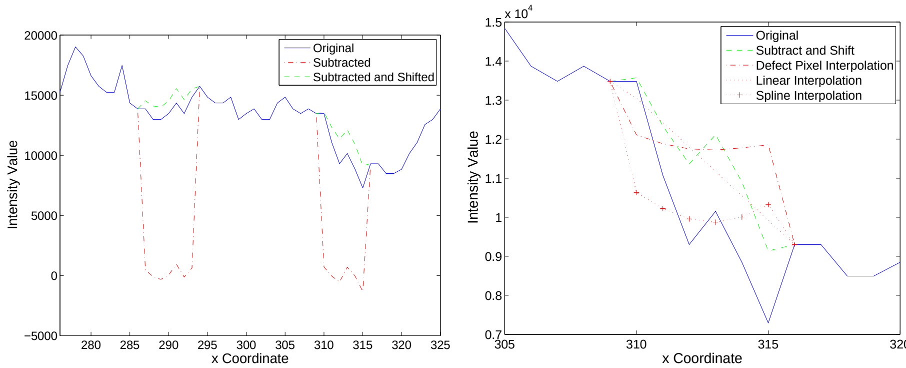
Fig. 2. Original and processed part from the catheter image. Line in (a) denotes area used for Fig. 4. Zoomed part is contrast enhanced to better show details. Arrows in zoomed part of (a) show points where catheter crosses the rib.



(a) Original (b) Interpolated

Fig. 3. Original and processed part from the pacemaker image.

Fig. 4. Intensity plots of interpolation results.



(a) Algorithm Steps (b) Comparison

image than the catheter phantom itself in the low-contrast test. But since this algorithm is by design highly dependent on the choice of "source material" to control the diffusion (c.f. [3]), further research on whether its performance in this environment can be improved is needed.

Figure 2 clearly shows that Subtract-and-Shift is able to reconstruct the information still contained inside the area of the catheter, e.g. parts of the ribs. As Fig. 4(b) confirms, the edge of the rib is reproduced (central spike), whereas the other interpolation methods do not reconstruct structure that corresponds to the underlying anatomy. The same can be observed for other parts of the image, where the catheter crosses tissue boundaries. Figure 3 show an equally good performance in the upper part of the pacemaker wire, albeit introducing artifacts in the bottom part.

For the future, we intend to produce ground-truth data from a physical phantom, to be able to compare our method to the others using RMSD or SDDI. Additionally, we intend to investigate the influence of different interpolation directions (as opposed to strictly horizontal) on the reconstruction result.

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