Non-iterative Compensation for Patient Motion in Dental CBCT Imaging

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***Abstract*—Cone Beam Computed Tomography is widely used in dentistry for diagnosis and treatment planning. However, it is susceptible to artifacts caused by patient movement during scanning. Manufacturers of cone beam CT systems have added mechanical fixations to prevent patient movement, but these are not completely rigid and still allow some movement. Researchers have tried to solve this problem with motion compensation algorithms. However, these solutions are often time consuming and only partially address the problem. This paper proposes a novel motion compensation approach based on a motion detection strategy to extract a motion-free subset of the scanned projections. A short-scan reconstruction is performed from the motion-free subset, which is used as a reference for the compensation algorithm, eliminating the need for multiple full-scan reconstructions at this stage. Motion compensation is performed by optimizing the motion parameters with a regularized 3D-2D image registration. The results show that the proposed algorithm can be used effectively to compensate for large and long-duration motions.**

***Index Terms*—Dental CBCT, motion compensation, non-iterative method, maxillofacial reconstruction**

I. Introduction

Cone Beam Computed Tomography (CBCT) is a 3D imaging modality commonly used in dentistry. CBCT systems have a long acquisition time and as a result, patient motion is likely to occur. It is estimated that approximately 21-42% of *in vivo* examinations exhibit motion artifacts [1]. To prevent motion, manufacturers of CBCT systems use mechanical fixation devices such as head support and chin rest. However, these devices have some degree of flexibility to allow for patient comfort, so motion cannot be completely avoided. Although several papers have been published on motion compensation, these algorithms typically require multiple reconstructions of the full set of projections, which is time consuming [2]–[4]. Another drawback is inconsistencies due to data truncation and scatter, which are common problems in CBCT imaging [5]. Also, most of these algorithms focus on compensating for relatively small motions such as jitter [6] or short-duration motions [3]. In this research, we propose a novel method to address these drawbacks. The proposed method is a non-iterative compensation and uses the Feldkamp-Davis-Kress (FDK) algorithm [7] for reference reconstruction. The goal of our method is to be able to compensate for large and long-duration rigid motions that significantly degrade reconstruction quality, without the need for multiple full-scan reconstructions in the compensation stage.

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II. Method

The proposed method works in two stages, motion detection followed by motion compensation. The motion detection algorithm used in this study is explained in our previous work [8]. Motion detection allows us to identify a motion-free subset of projections from the full scan (section III-A). Spin-Neto et al. [9] showed that larger motions that affect reconstruction quality are confined to a smaller region. Therefore, in most cases, there exists a motion-free subset of projections. The focus of this paper is on the second stage of the proposed method (motion compensation).

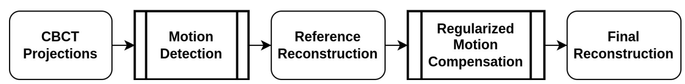


Fig. 1: Pipeline of the proposed method

A reference short-scan reconstruction is performed using the motion-free subset of the projections. Each motion-affected projection is registered to a synthetic image generated by reprojecting the reference reconstruction. Prior to reprojection, the reference reconstruction is regularized to increase the robustness of the registration (section II-A). Registration is performed by optimizing the similarity score obtained using the cost function explained in section II-B. This process is repeated by perturbing the motion parameters until convergence. Since the same reference reconstruction is used for all motion-affected projections, the optimizer can be run in parallel for multiple projections to save time. A final high-quality reconstruction is performed using the estimated motion parameters.

A. Regularization

The original reference reconstruction is of lower quality for three reasons: i) only a subset of the projections is used for reconstruction, ii) the projections contain very low contrast structures, and iii) the projections are noisy due to low X-ray doses. For these reasons, a direct comparison between original projections and reprojected ones is difficult. We therefore focus on the most prominent structures, such as jawbones and teeth. To extract these structures, threshold-based segmentation is effective due to the large difference in attenuation between soft and hard tissues. Therefore, in the regularization step, all attenuation values in the reference reconstruction above a certain threshold are replaced by a constant value close to the average attenuation of the hard tissues. The values below the threshold are removed.

B. Similarity Cost Function

After the regularization step, the extracted strong edges are reprojected to generate the synthetic projections. We can therefore use a gradient strategy for image registration. We define our cost function $G(r, a)$ as the sum of the minima of the gradient magnitudes computed for corresponding pixels of the synthetic image (r) and the actual image (a), multiplied by a weighting function w:

$$G(r,a) = \sum_{(\mathbf{x},\mathbf{x}')\in(r\,\cap\,a)} w_{\mathbf{x},\mathbf{x}'}\ \min\left(|\nabla\mathbf{x}|, |\nabla\mathbf{x}'|\right) \quad (1)$$

where $\mathbf{x}$ and $\mathbf{x}'$ denote the corresponding sample points (pixels) in r and a respectively. w is the cosine of the angle between the two gradients:

$$w_{\mathbf{x},\mathbf{x}'} = \cos(\theta) = \frac{\nabla\mathbf{x}\cdot\nabla\mathbf{x}'}{|\nabla\mathbf{x}|\,|\nabla\mathbf{x}'|}. \quad (2)$$

III. Implementation & Results

A. Data

In this experiment, we used a phantom containing the skull and teeth of a deceased patient, cast in a uniform plastic resin that approximates the X-ray attenuation of human soft tissue. Realistic motions were simulated using the strategy described in our previous paper [8]. Three **returning motions** (**nodding**, **tilting** and **lateral rotation**) (Table I) were simulated for a duration of 6 seconds (one quarter) for a full 360° scan of 24 seconds. Because of the mechanical fixations, e.g. head support, it is realistic to assume that the patient returns to the original position after the movement, so that it is possible to find at least one motion-free subset of 180°, which is sufficient for a good reference reconstruction.

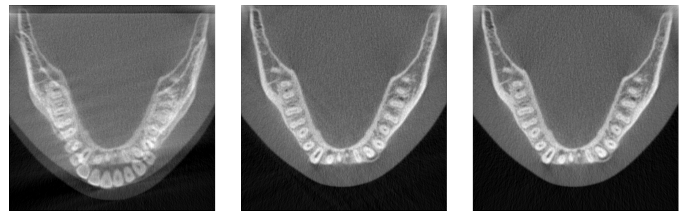
To test the robustness of the method, a **non-returning abrupt motion** was also simulated, where the patient remains in one pose for part (almost half) of the scan, and then suddenly moves to another pose and remains still for the rest of the scan. This created double contours in the reconstruction (Fig. 2a), which is one of the most difficult cases to compensate for. To assess the quality of the final reconstruction, a motion-free reconstruction of the 360° scan was performed as a ground truth for comparison (Fig. 2c).

TABLE I: SSIM and RMSE values for different motions: MA = motion-affected, MC = motion-compensated.

	SSIM (↑)			RMSE ($\times10^{-2}$)(↓)		
Motion type	MA	MC	Diff %	MA	MC	Diff %
Nodding	0.895	0.956	+6.1	2.248	0.934	-1.3
Tilting	0.880	0.917	+3.7	2.833	1.228	-1.6
Lateral rotation	0.877	0.884	+0.7	3.191	2.378	-0.8
Abrupt motion	0.770	0.941	+17.1	5.864	0.995	-4.9

B. Results

The reconstruction libraries were provided by See Through S.r.l. Experiments were performed using Powell's conjugate direction optimizer. The evaluation of the final reconstruction quality is performed using the Structural Similarity Index Measure (SSIM) and the Root-Mean-Square Error (RMSE), which are summarized in Table I. A comparison between the motion-affected, motion-compensated, and ground-truth reconstructions for the abrupt motion is shown in Fig. 2. The results show that the proposed method can effectively compensate for artifacts induced by long-duration motion, with only minor artifacts remaining.



(a) Motion-affected (b) Compensated (c) Ground truth

Fig. 2: Results for non-returning abrupt motion

IV. Conclusion

Our method uses a non-iterative approach that effectively compensates even for large and long-duration motions. By detecting motion and applying appropriate regularization to the reference reconstruction, our method can produce high-quality results without the need for multiple full-scan reconstructions in the compensation stage. In the future, we plan to work on a refinement strategy to further improve the quality of the reconstruction by minimizing the remaining small artifacts. Tests with more complex motions and clinical data need to be performed to evaluate the robustness of the proposed method in different scenarios.

References

[1] R. Spin-Neto, L. H. Matzen, L. Schropp, E. Gotfredsen, and A. Wenzel, "Factors affecting patient movement and re-exposure in cone beam computed tomography examination," *Oral surgery, oral medicine, oral pathology and oral radiology*, vol. 119, no. 5, pp. 572–578, 2015.

[2] S. Maur, D. Stsepankou, and J. Hesser, "Cbct auto-calibration by contour registration," in *Medical Imaging 2019: Physics of Medical Imaging*, vol. 10948. SPIE, 2019, pp. 413–421.

[3] T. Sun, R. Jacobs, R. Pauwels, E. Tijskens, R. Fulton, and J. Nuyts, "A motion correction approach for oral and maxillofacial cone-beam ct imaging," *Physics in Medicine & Biology*, vol. 66, no. 12, p. 125008, 2021.

[4] L. Birklein, S. Niebler, E. Schömer, R. Brylka, U. Schwanecke, and R. Schulze, "Motion correction for separate mandibular and cranial movements in cone beam ct reconstructions," *Medical physics*, 2023.

[5] T. Würfl, M. Hoffmann, A. Aichert, A. K. Maier, N. Maaß, and F. Dennerlein, "Calibration-free beam hardening reduction in x-ray cbct using the epipolar consistency condition and physical constraints," *Medical physics*, vol. 46, no. 12, pp. e810–e822, 2019.

[6] F. Dennerlein and A. Jerebko, "Geometric jitter compensation in cone-beam ct through registration of directly and indirectly filtered projections," in *2012 IEEE Nuclear Science Symposium and Medical Imaging Conference Record (NSS/MIC)*. IEEE, 2012, pp. 2892–2895.

[7] L. A. Feldkamp, L. C. Davis, and J. W. Kress, "Practical cone-beam algorithm," *Josa a*, vol. 1, no. 6, pp. 612–619, 1984.

[8] A. S. R. Asraf Ali, A. Fusiello, C. Landi, C. Sarti, and A. A. P. Siswadi, "Motion artifacts detection in short-scan dental cbct reconstructions," *arXiv preprint arXiv:2304.10154*, 2023.

[9] R. Spin-Neto, L. H. Matzen, L. W. Schropp, T. S. Sørensen, and A. Wenzel, "An ex vivo study of automated motion artefact correction and the impact on cone beam ct image quality and interpretability," *Dentomaxillofacial Radiology*, vol. 47, no. 5, p. 20180013, 2018.