Self-Calibration and Simultaneous Motion Estimation for C-Arm CT Using Fiducial Markers

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Abstract. C-arm cone-beam CT systems have an increasing popularity in the clinical environment due to their highly flexible scan trajectories. Recent work used these systems to acquire images of the knee joint under weight-bearing conditions. During the scan, the patient is in a standing or in a squatting position and is likely to show involuntary motion, which corrupts image reconstruction. The state-of-the-art fully automatic motion compensation relies on fiducial markers for motion estimation. Due to the not reproducible horizontal trajectory, the system has to be calibrated with a calibration phantom before or after each scan. In this work we present a method to incorporate a self-calibration into the existing motion compensation framework without the need of prior geometric calibration. Quantitative and qualitative evaluations on a numerical phantom as well as clinical data, show superior results compared to the current state-of-the-art method. Moreover, the clinical workflow is improved, as a dedicated system calibration for weight-bearing acquisitions is no longer required.

1 Introduction

The high flexibility of C-arm cone-beam CT (CBCT) systems allow their usage in a wide range of new applications. Recently, these systems have been used to acquire data from knee joints under weight-bearing conditions [1, 2, 3]. For this purpose, the C-arm has to move on a horizontal trajectory around the standing patient. During the scan, involuntary patient motion can occur, which causes blurring, double edges and streaks in the 3D image reconstruction. Estimation and compensation of patient motion improves the quality of the reconstructed images. The state-of-the-art method estimates motion based on fiducial markers, which are attached to the patients knee [4].

However, the method requires a time consuming calibration with a calibration phantom for each scan, since the horizontal trajectory is not supported and thus, not reliably reproducible with the used C-arm system [5]. A self-calibration
approach would be beneficial in such a setting. Current approaches can be di-
vided into methods, which use external tools, like calibration markers or tracking
systems [6], or rely only on the acquired data [7, 8].

The proposed approach in this work uses fiducial markers to calibrate the
system, while simultaneously compensating for the patient’s motion. Hence,
dedicated time consuming calibration scans are dispensable.

2 Materials and methods

2.1 State-of-the-art motion compensation framework
The state-of-the-art motion estimation framework is introduced in the follow-
ing [4, 3]. First, a reference 3D marker position is estimated for each marker by
backprojecting the detected 2D marker positions into the volume. Then, the 3D
reference positions are registered with the detected 2D positions [9]. Afterwards,
the rigid motion consisting of three translation and three rotation parameter is
estimated, such that the reprojection error (RPE) of the projected 3D reference
marker positions on the 2D detected marker is minimized

$$\arg \min_\alpha f(\alpha) = \arg \min_\alpha \frac{1}{2} \sum_{i=1}^{M} \sum_{j=1}^{J} ||h(n) - u_{ij}||^2_2$$

$$n = (n_1 \ n_2 \ n_3)^T = P_j \cdot M_j(\alpha) \cdot (v_i \ 1)^T$$

where vector $\alpha \in \mathbb{R}^{6J}$ contains three rotation and translation parameters for
each projection. The matrix $M_j(\alpha)$ applies the rigid motion to the calibrated
projection matrix $P_j \in \mathbb{R}^{3 \times 4}$ for projection $j$. The estimated i-th 3D marker
position is given by $v_i$ and the corresponding detected 2D position on the j-th
projection is given by $u_{ij}$. The function $h : \mathbb{R}^3 \mapsto \mathbb{R}^2$ describes the mapping
from 3D homogeneous coordinates to 2D coordinates, i.e., a division by the
third component $h(n) = \left( \frac{n_1}{n_3} \ \frac{n_2}{n_3} \right)^T$. In a last step, motion is compensated by
incorporating the estimated motion into the projection matrices and using these
updated projection matrices for the reconstruction [3, 4].

2.2 Joint motion estimation and system calibration
We face two problems if no calibration scan is performed and thus no initial esti-
mation of the projection matrices is available. Valid system matrices are needed
for the backprojection in the marker detection and for the forward projection to
evaluate the objective function. To overcome the missing calibration, we propose
to initialize with an ideal circular trajectory and to decompose the projection
matrices into an extrinsic and intrinsic matrix, such that the intrinsic parameter
estimation can be incorporated in the estimation process.

Initialization. The projection matrices $P_j$ are initialized with the ideal horizon-
tal circular trajectory based on the systems properties. The 3D marker detection
and the evaluation of the objective function can be performed sufficiently well.