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Tumor localization and dose planning

Stochastic triangulation for prostate positioning during radiotherapy using short CBCT arcs ☆

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ABSTRACT

Background and purpose: Fast and reliable tumor localization is an important part of today's radiotherapy utilizing new delivery techniques. This proof-of-principle study demonstrates the use of a method called herein 'stochastic triangulation' for this purpose. Stochastic triangulation uses very short imaging arcs and a few projections.

Materials and methods: A stochastic Maximum A Posteriori (MAP) estimator is proposed based on an uncertainty-driven model of the acquisition geometry and inter-/intra-fractional deformable anatomy. The application of this method was designed to use the available linac-mounted cone-beam computed tomography (CBCT) and/or electronic portal imaging devices (EPID) for the patient setup based on short imaging arcs. For the proof-of-principle clinical demonstration, the MAP estimator was applied to 5 CBCT scans of a prostate cancer patient with 2 implanted gold markers. Estimation was performed for several (18) very short imaging arcs of 5° with 10 projections resulting in 90 estimations.

Results: Short-arc stochastic triangulation led to residual radial errors compared to manual inspection with a mean value of 1.4 mm and a standard deviation of 0.9 mm (median 1.2 mm, maximum 3.8 mm) averaged over imaging directions all around the patient. Furthermore, abrupt intra-fractional motion of up to 10 mm resulted in radial errors with a mean value of 1.8 mm and a standard deviation of 1.1 mm (median 1.5 mm, maximum 5.6 mm). Slow periodic intra-fractional motions in the range of 12 mm resulted in radial errors with a mean value of 1.8 mm and a standard deviation of 1.1 mm (median 1.6 mm, maximum 4.7 mm).

Conclusion: Based on this study, the proposed stochastic method is fast, robust and can be used for inter- as well as intra-fractional target localization using current CBCT units.

Radiotherapy patient setup and verification in the prone and supine positions is an ongoing issue [1–14]. Reliability and reproducibility of setup for pelvic radiotherapy treatments are important both for inter- and intra-fractional variability of the anatomy. Specifically in prostate patients, the location of both the prostate and rectum with respect to the treatment iso-center is essential for intensity modulated radiotherapy (IMRT) and volumetric intensity modulated arc therapy (VMAT) treatments which utilize steep dose gradients [5,7,8]. The prostate can be accurately localized in cone-beam computed tomography (CBCT) images taken before the treatment [14]. However, a practical verification of prostate location during the treatment is not easy in real time using the available linac-mounted imaging modalities [15,18]. Verification of prostate location could in principle be attempted based on the analysis of images from an electronic portal imaging device (EPID) or an orthogonally mounted kV imager often used for CBCT acquisitions taken during the IMRT/VMAT delivery. However, tracking prostate location in such images with robust image analysis algorithms is still an open problem [15,16].

In this paper, we present a robust approach to image-guided tracking of the prostate during radiotherapy which explicitly takes into account the possibility of time dependent shifts and deformations of the prostate in a stochastic (Bayesian) model. In this model, *prior knowledge* about the setup errors based on the initial setup with the in-room lasers and possible image guided localization errors is employed to improve the accuracy of prostate localization and also the robustness of the algorithm. The stochastic model is unique in that it takes the radiographs which were obtained during treatment as direct input. It does so without the need for image reconstruction (e.g., CBCT or CB tomosynthesis) or the need for determination of locations of specific markers in each projection. Furthermore, it performs a fast numerical computation to

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determine the optimal shifts/rotations utilizing a forward triangulation formula. This is why we call our model "stochastic triangulation". Triangulation is a method of determining coordinates of an object or more complex landscape from different viewing perspectives. Our method is related to stereoscopic imaging and localization [17] but goes beyond the simple geometry used for these methods. Other similar approaches try to work with a single (or a few very similar) view and are labeled as monoscopic imaging techniques [18–20]. To date there are no comparable algorithmic approaches that allow the incorporation of various sources of *prior information* for the patient setup in an automatic fashion and a comprehensive mathematical framework. This proof-of-principle study for the prostate location is of high interest for future clinical application of this method to other treatment sites.

Methods

Maximum A Posteriori estimation for patient positioning

The estimation of the initial patient setup errors was based on a stochastic model of a deformable anatomy, previously introduced by the authors [21,22]. The intent was to estimate the position of the treatment target by the use of implanted gold markers, which spatially defined the target. As these markers could change their positions individually due to the deformation of the anatomy, more than one single marker was utilized. Further, to compensate for low-quality projections, due to noise or overlaying structures, several projections were used at once. The estimation of the target position (described as a reference point $\vec{T}$) was associated with different uncertainties of the observation, which were modeled by probability density functions (PDFs). Consequently, this model combines the projective geometry (cone-beam geometry in case of CBCT) and spatial probability clouds for the following:

- The range of the initial setup errors after positioning the patient with the aid of the in-room laser system, denoted with $\pi_{\vec{T}}$,
- The possible positions of implanted markers relative to an arbitrary reference point (allowing displacements, rotations and general deformations of the tissue), denoted with $\pi_{\vec{F}_l}$, and
- Geometric uncertainties in the acquired projection images, such as the blurry appearance of these markers, and the pixelation and uncertainties related to image processing, denoted with $\pi_{\Delta\vec{U}}$.

For an illustration of these PDFs, see the Supplement. In this work, the proposed stochastic triangulation method was applied for the first time to a series of clinically acquired CBCT scans of a prostate cancer patient, utilizing implanted gold markers as a surrogate of the PTV for localization purposes. The focus of our study was the use of very short arcs of down to 5° for which a robust estimation of the current translational setup error was determined. For mathematical details see the Supplement.

Several aspects made this approach appealing for estimating setup errors, such as

- The selection of arbitrary imaging angles and number of projections (using greater equal to 2 radiographs in very short arcs down to 5°),
- Direct incorporation of deformations and individual displacements of the markers relative to each other by actively modeling probability clouds of the 3D marker locations, and
- Segmentation and labeling/classification of the markers in the projections in a pre-processing step were not needed (just a general marker-to-tissue contrast enhancement was performed in the projection images). These images after the contrast enhancement are denoted by m_n for projection number n.

A technical but not less important advantage with practical impact is that the whole methodology was modeled in a single stochastic framework, which allows to calculate expected accuracies of the estimation prior to the measurement [21], and which can be easily adapted to other estimation scenarios.

The numerical evaluation of Eq. (4) in the Supplement with a Matlab/C code took 2–3 min on the test computer (Pentium 3 GHz, 2 GB RAM). This can be improved significantly by more advanced implementations, optimization algorithms and more adapted hardware in the future.

Prostate patient with gold markers

In this work, we wanted to validate the MAP estimator (see the Supplement) by applying it to CBCT scans of a prostate with implanted gold markers (see Fig. 1). The two selected gold markers placed inside the prostate were approximately 0.9 cm and 1.8 cm long and 0.1 cm in diameter. On average a set of 665 CBCT projections was acquired for every patient setup with a Varian OBI system in a 360°-arc, leading to an average projection spacing of 0.54°. The two gold markers were visible in all projections, with a lower contrast in lateral and a higher contrast in posterior–anterior views (see Fig. 1). In total, 5 CBCT scans (and their projections) of the prostate were acquired during the course of one month, which resulted in a data source of 3350 projections, each with a 1024×768 pixel resolution. In these 5 CBCT scans, radial distance differences of the two markers in the range of 1–2 mm were manually observed, indicating the deformability of the prostate.

Determination of prior knowledge as probability density functions

Prior knowledge was introduced in the form of probability density functions (PDFs) or, more figuratively, probability clouds. In this work, the prior knowledge about the initial setup error ($\pi_{\vec{T}}$) was taken to be a Gaussian distribution with a standard deviation of 10 mm around the reference point (which coincided with the iso-center of the plan). Similarly, for the detector error ($\pi_{\Delta\vec{U}}$), a Gaussian distribution with a fixed standard deviation of 0.75 mm was defined, which was equal to the approximate magnitude of two pixel lengths in the projection. For the potential 3D marker locations ($\pi_{\vec{F}_l}$), the effort was divided into two steps. Step one was finding a reference appearance/characteristic of the markers of the first of the five setups as space curves relative to the iso-center. This was done by finding a polynomial 3D space curve for every marker in this setup based on several 2D projections. Manually defining marker end-points in every projection and utilizing Eq. (3) in the Supplement, led to an overdetermined system of linear equations for the polynomial coefficients which was solved by least squares. In clinical practice, a potentially easier way could be chosen, as a planning CT is available and potentially the reference appearance of each marker can be determined by a threshold method as long as no sincere metal artifacts in the reconstruction prohibit this, e.g. see Ref. [23]. Step two consisted of convolving the 3D space curves with a 2 mm standard deviation Gaussian distribution. This convolution took place in order to purposefully remove the exact spatial information of the markers of the first setup according to the mathematical framework described in the Supplement. This in turn enabled us to include potential displacements and deformations of the markers during the course of the treatment, resulting in the marker PDFs which fit to a wide range of potential marker locations. The value of the standard deviation was not a sensitive parameter and was selected based on the evaluation of the 5 setup scans.