Sparse Active Triangulation Grids for Respiratory Motion Management

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In radiation therapy, tracking the patient's non-rigid torso deformation during dose delivery holds potential to improve accuracy and efficiency using model-based tumor motion compensation. Conventional solutions rely on a 1-D respiration surrogate and are subject to model uncertainties. Instead, the proposed system acquires sparse 3-D measurement grids and recovers a multi-dimensional surrogate.

1 Introduction

The management of respiratory motion poses a challenge to a variety of medical applications and holds potential for enhanced tomographic reconstruction, computer-assisted interventions and radiation therapy (RT) treatment. In the field of radiation oncology, studies have shown that external body motion correlates with the internal tumor position. Hence, based on a patient-specific correlation model learned prior to the first fraction, the tumor location can be inferred from an external surrogate during treatment [1, 2]. The underlying clinical workflow is illustrated in Fig. 1. In contrast to conventional respiratory gating techniques that entail a low duty cycle, intra-fractional tumor tracking and motion compensation potentially allows for continuous treatment.

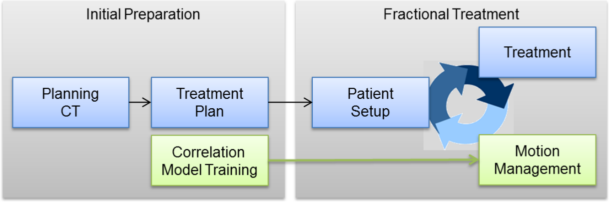

Fig. 1 *Flowchart of the clinical workflow for RT motion management using an initially learned correlation model.*

Clinically available solutions for motion compensation rely on a single 1-D respiratory surrogate and exhibit a limited level of accuracy due to inter-cycle variations. Recent work indicated that considering multiple regions would yield an enhanced model [1]. Hence, we propose a novel solution based on a single-shot active triangulation sensor [3] that acquires a sparse grid of 3-D measurement lines in real time, using two perpendicular laser line pattern projection systems. Building on non-rigid point set registration, the non-rigid displacement field representing the elastic torso deformation with respect to a reference dataset is recovered. This displacement field can eventually be used as a multi-dimensional respiration surrogate for model-based tumor tracking and motion compensation.

2 Setup and Measurement Principle

Originally, the optical measurement principle we apply in this work was introduced as a modality that allows to reconstruct dense 3-D surface models by freely moving the hand-held device around an object (*Flying Triangulation* [3, 4]). Based on the principle of light sectioning with multiple-line patterns, the single-shot sensor acquires a series of sparse 3-D views from different perspectives in a marker-less manner. Let us remark that each view holds dense 3-D data along the projected lines only. Simultaneously, consecutive sparse measurement grids are aligned in real-time using a dedicated (rigid) point set registration algorithm, eventually recovering a dense and accurate 3-D surface model. The measurement principle is scalable and a sensor for reconstructing objects in the meter range (human bodies, for instance) was introduced recently [4].

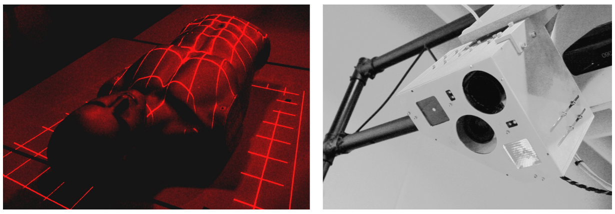

Fig. 2 *Stationary mounted Flying Triangulation sensor (right), acquiring sparse active triangulation data of a male torso phantom (left).*

In this work, instead, we stationary mount the active triangulation sensor and acquire a series of sparse 3-D measurements of a moving object from the same perspective. For the proposed application in radiation therapy, where the device is ceiling-mounted above the RT patient table, this allows to capture the elastic deformation of the patient's torso on a grid-like sampling (c.f. Fig. 2) in real-time. Let us remark that the sparseness of the body sensor measurement grid (for details see Sec. 4) is sufficient for tracking the surface deformation of a human torso, typically exhibiting a low-frequent surface topology.

3 Tracking the Non-Rigid Torso Deformation

Both the pre-fractional generation of a patient-specific external-internal correlation model and its intra-fractional application for tumor motion compensation requires to recover the non-rigid displacement field that maps the instantaneous point set to a given reference (Fig. 3). In this work, we employ the coherent point drift (CPD) algorithm [5] for this task.

CPD is a non-rigid point set registration method that considers the alignment of two point sets as a probability density estimation problem. Basically, it interprets the moving point set as Gaussian mixture model (GMM) centroids that are fit to the reference point set by maximizing the likelihood in an expectation-maximization framework. To ensure the motion field to be smooth, implying preservation of topological structure, the GMM centroids are constrained to move coherently (regularization).

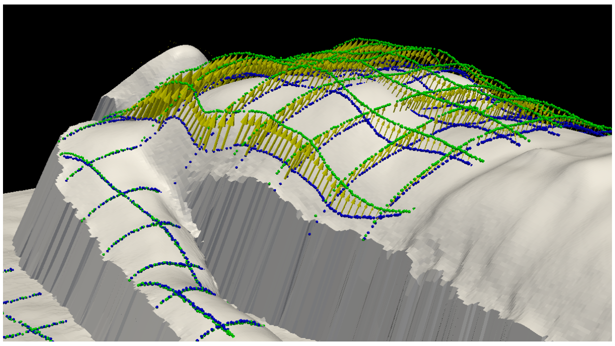

Fig. 3 *Non-rigid motion field (yellow glyphs) between instantaneous respiration phase (fully inhale, green) and reference phase (fully exhale, blue) estimated by CPD point set registration. For visual guidance, a dense surface scan is shown additionally.*

4 Experiments and Results

For validation of the method, we have performed a study on healthy subjects, subsequently performing abdominal and thoracic respiration, respectively. Experimental data were acquired with a body-scale triangulation sensor [4], capturing a sparse grid of 11×10 sampling lines at 30 Hz, using two perpendicular laser line pattern projection systems (160 mW) and a 1024×768 px resolution CCD chip. The target measurement volume was $800 \times 800 \times 350$ mm^3 with a mean measurement uncertainty of $\sigma = 0.39$ mm.

First, the system allows to directly observe the spatial extent of respiratory motion over time along each projection line, see Fig. 4. Second, using CPD-based point set registration, the non-rigid motion field transforming a reference point set to the instantaneous sampling data can be estimated, see Fig. 3.

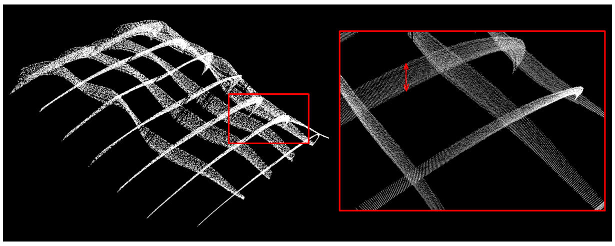

Fig. 4 *Capturing sparse triangulation grids over time allows to analyze the spatial range of respiratory motion.*

5 Conclusions and Outlook

In this work, we have presented a system that is capable of acquiring a multi-dimensional respiration surrogate for tumor motion compensation in radiation therapy. Using sparse triangulation grids in combination with non-rigid point set registration, the proposed system can recover and track the elastic deformation of the patient's torso. Based on an initially learned motion model, the estimated motion field can be applied for motion compensation during dose delivery. Beyond RT, the approach holds great potential for a variety of medical applications.

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